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VOL. 39 NO. 349 JANUARY 1953

THE INSTITUTE OF PETROLEUM

AN Ordinary General Meeting of the Institute of Petroleum was held at 26 Portland Place, London, W.1, on 10 September 1952, the President, Mr H. S. Gibson, C.B.E., in the Chair.

THE PRESIDENT: It is a very great pleasure to be able to introduce Mr Paxton, of the Iraq Petroleum Company—my own company—to read a paper on drilling muds.

I expect there are many here whose minds go back to the very early days of rotary drilling, a system which had long been the aim of drilling experts. Percussion drilling had been in use for many years, but when the depth of wells began to exceed about 4000 ft the percussion system began to fail, one very serious difficulty being that the extension and contraction of the drill line with each stroke of the beam reduced the effect of the bit on the bottom of the hole. The rotary system had to employ a fluid to bring the rock cuttings to the surface. In the beginning, water was used, but was soon replaced by mud. Many difficulties arose, and those who can remember the early days will recall how the drill became stuck, the cuttings settled back very rapidly around the bit, and there was a " fishing job " in hand. The pressure in the hole had to be equal to or greater than that around it, for otherwise the well would blow in, and a very difficult situation could arise.

I think the first step that drillers began to take was towards making the mud column heavier, and for that purpose they began to use materials such as barytes, hæmatite, or anything else that was suitable. Often they used any local mud or other material that was handy, and it came to be called " drilling mud." As time went on, however, that material had to be modified. For example, barytes tended to settle out very easily and rapidly, and materials had to be put into the mud to condition it so that the heavy material did not settle out so quickly, and bentonite came into use.

That was only a beginning, and in the last twenty to twenty-five years very great progress indeed has been made in the development of " drilling fluids "—that is the name that should be applied to them. No longer is the material a mud. It is one of the most expensive things that has been devised yet, and it is so easily lost from the bottom of the hole. It is not unknown for the materials composing the mud in a single well to cost more than £40,000, that is more than the casing put into the hole. On the other hand, the drilling fluid has enabled wells to be drilled to great depths through most difficult formations, and also has enabled very high pressures to be controlled to enable producing formations to be entered without sealing off the oil and gas from the holes. In short, the progress made over the last twenty years or so in drilling can be ascribed very largely indeed to the improvement in drilling fluids.

In the Iraq Petroleum Company Mr Paxton has been concerned with the problems connected with drilling fluids for rather more than twenty years. He has been very close to the work all the time; in fact, he has contributed

very largely to the success which the Company has achieved in tackling many difficult drilling problems. This evening we are to hear him present a most interesting paper covering the progress that has been made in that time and the position which has now been reached.

Mr A. W. Paxton then presented the following paper :

MUD CONTROL IN THE FIELDS OF THE IRAQ PETROLEUM AND ASSOCIATED COMPANIES

By A. W. Paxton *

Synopsis

The varying formations which occur in the fields of the Iraq Petroleum and Associated Companies form the logical background to mud development, which is outlined on considerations of suspensive ability, practical filtrate/viscosity relationship, and the modifying influence of subsurface conditions. The limitations, advantages, and local application of bentonite and emulsion muds modified by starch and lime treatment are contrasted, and reference is made to drilling with salt water.

Maintenance and control of muds under the influence of disturbing physical and chemical factors is outlined with special reference to mud thinners. Attention is then given to mud losses in fractured formation. The final section deals with factors influencing mud economy.

Historical Introduction

Largely owing to the discovery in 1929 of the shallow Kirkuk field, where the drilling of wells is relatively free from the problems which make mud control necessary, it was not until 1939, when the Company extended exploratory drilling to new areas in northwestern Iraq and to the Qatar peninsula on the Persian Gulf, that organized interest in the subject was introduced. Owing to the outbreak of war, however, and the restriction of supplies of mud materials, development was confined to the use of locally available products, notably gum tragacanth. In 1941 drilling activity in Iraq was brought to a standstill by political events, and in the following year work in Qatar also ceased. For the remainder of the war years all work on drilling muds was confined to the laboratory, where efforts were made to keep pace with new developments. After a period of inevitable delay for the assembly of necessary supplies of materials and equipment, an extensive programme of exploration and development was launched in 1947. Fields have now been proved and actively developed in the Mosul Petroleum Co., Iraq Petroleum Co., and Basrah Petroleum Co. areas of Iraq and in the Qatar peninsula, and exploration has been carried out in other areas, notably Syria and the Trucial Coast.

Formation Encountered in the Various Areas

Since mud programmes are planned and modified to deal with problems originating in the subsurface conditions encountered during drilling, it is appropriate to review briefly the general nature of formations which occur

* Iraq Petroleum Co. Ltd.

in the areas under consideration. The various formations encountered in three developed fields are summarized in Table I; exploratory areas add further variety to the drilling conditions experienced.

Limestones, marls, and calcareous shales predominate, and are common to all the fields, although thickness ranges from a few hundred to several thousand feet; this applies not only to different formations in the same locality, but also to formations of similar age in more widely dispersed areas. These formations also show considerable variation of characteristics, such as porosity and fracturing in the case of the limestones, or friability and dispersability in that of the shales. Variations are more sharply contrasted in the case of formations of differing geological age, but the characteristics of deposits of equivalent age, although generally similar, may differ markedly in degree. For example, the porosity of the Upper Cretaceous Ain-Zalah limestone differs considerably from that of Lower Cretaceous limestone in the Dukhan field. Likewise the Dohuk shale of Ain Zalah is much more friable than that of the Lower Cretaceous shale of Dukhan. Illustrative of difference of degree is the Middle Cretaceous dolomite, which shows considerable variations of fracturing and porosity from one locality to another. In a similar way the Dohuk shale of the Ain Zalah field is much more liable to slough in some wells than others, and even in the same well shows marked differences between the upper and lower portions of the same formation.

Anhydrite is also common to all areas, but is present to a much more limited extent. It occurs frequently in beds of 50 to 100 ft, and only occasionally exceeds 400 to 500 ft as in the Rus Anhydrite of the Zubair field. It may alternate with limestone in a series of thin layers, as in the Arab Zone of the Dukhan field, or with salt as in the Miocene formations of Kirkuk. Gypsum characterizes some of the Miocene formations of Syria and Ain Zalah.

Sands of Miocene age occur in the Zubair field, but formations of Lower Cretaceous age are more widely encountered, as in the Zubair and Dukhan fields and in exploratory wells drilled in Syria. Sand formations are also associated with Permian and Carboniferous deposits in the Syrian wells.

Salt-bearing formations of Tertiary age occur in considerable thickness in the Trucial Coast area, and are also associated with the Miocene deposits of the Kirkuk field and those of similar geological age in Syria.

These various formations constitute the logical background to the development of muds suitable for their penetration.

The Basis and Development of Drilling Muds

The preparation, maintenance, and control of drilling muds involves the selection and combination of components from a series of major groups which may be classified as :—

(*a*) suspending materials;
(*b*) weighting materials;
(*c*) filtrate reducers or wall builders;
(*d*) viscosity reducers, or more accurately, gel retarders;
(*e*) pH control chemicals;
(*f*) plugging or sealing agents.

Some of these groups permit of a wider, some of a more limited, choice or range of materials within the group. Suspending agents are common to all drilling muds, filtrate reducers to most; viscosity reducers are generally necessary for mud control; the need for the presence of components from the remaining groups is dependent on specific conditions. Beyond the indispensable quality of suspension, governed by saline or non-saline conditions, the following conditions determine further modification of mud within the experience covered by this paper :—

(*a*) porous limestones with associated mud ringing troubles;
(*b*) loss of circulation;
(*c*) sloughing shales;
(*d*) calcium contamination from the drilling of anhydrite;
(*e*) gas and air cutting;
(*f*) high-temperature effects in deep wells.

The first essential in the preparation of any satisfactory drilling mud, irrespective of how it may be modified to deal with specific requirements, is to ensure the stable suspension of homogeneously dispersed materials, *i.e.*, mud should be free from a tendency of its solid components to settle out under static conditions. It should fulfil the role of suspending formation cuttings under circulating conditions until they are removed on the vibrating screens, and also under static conditions, thus preventing them from settling and packing around the top of the drill collars—a likely cause of sticking tools. The mud should also be capable of maintaining in suspension any weighting material subsequently added to control pressure. These qualities require the development of a certain amount of structural viscosity in the dispersed mud solids, and this should be preferably thixotropic. Unfortunately, no useful supplies of suspensive material are forthcoming from outcropping shales occurring in the widely dispersed areas covered by the Company's concessions, with one exception in Qatar, in consequence of which extensive use has to be made of imported material.

The choice of the type of clay to be used depends on whether the make-up water is saline or non-saline, and also on drilling conditions. For non-saline conditions bentonitic clays are used, characterized by the clay minerals Montmorillonite and Beidellite. Salt, however, suppresses hydration and swelling of bentonite, with a resulting adverse effect on mud characteristics; therefore salt-resistant clays, characterized by the clay mineral Attapulgite, have to be used under all saline conditions. This type of material is most extensively used for exploratory wells on the Trucial Coast, where saline conditions predominate, and to a lesser extent in the Dukhan field. The overall consumption figures for the period May 1947 to January 1952 were : bentonite, 4767 tons; salt-resistant clay, 733 tons.

The next step in the development of a mud after consideration of adequate suspension involves the important balance of filtration and viscosity characteristics, which have to be kept in mind simultaneously. A material is frequently rejected as unsuitable for mud preparation because the filtrate required can be obtained only at the expense of an undesirably high viscosity. As concentration of bentonite increases, viscosity rises and filtrate falls, but the rate as well as the degree of change varies markedly

with the particular clay in use. This is clearly illustrated by reference to Figs 1 and 1(*a*), which contrast the filtrate/concentration and viscosity/concentration relationships of two types of bentonite which are extensively used. In general, unmodified bentonitic muds are not used to produce filtrates below 10 ml because of disproportionately high viscosity or gel characteristics at the concentrations required to produce them. In the case of salt-resistant clay muds, the filtration characteristic is unsatisfactorily high for all usable concentrations (see Figs 1 and 1 (*a*)), and for most conditions requires modification.

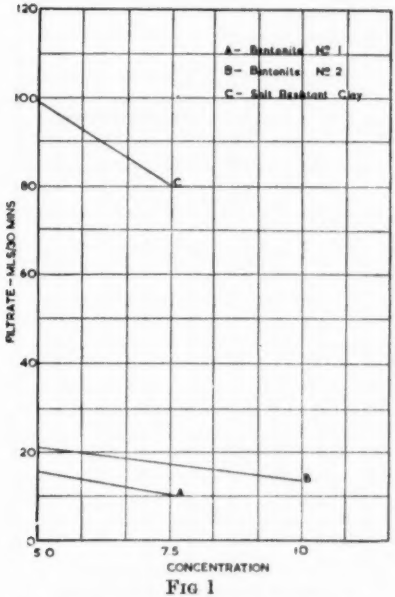

FIG 1

FILTRATES OF BENTONITIC AND SALT-RESISTANT CLAY MUDS

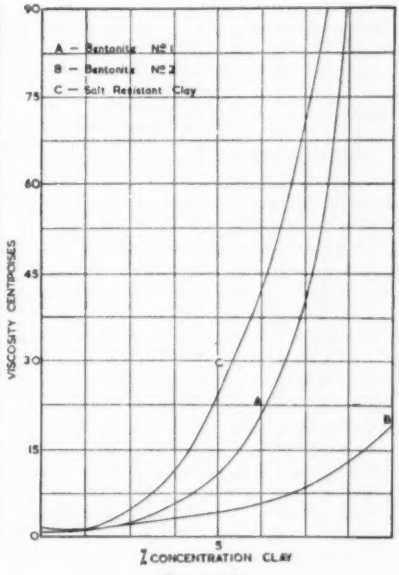

FIG 1 (*a*)

VISCOSITIES OF BENTONITIC AND SALT-RESISTANT CLAY MUDS

Conditions encountered during drilling determine the desirable filtration characteristic. For straightforward drilling in average limestone or marl of low porosity a filtrate of 10 to 20 ml is quite adequate, and may be considerably exceeded without incurring difficulty. The drilling of shale with a tendency to slough, which often causes sticking of tools, or of porous limestones on which a mud with too high a filtrate deposits a proportionately thick cake of solids (which also impedes the withdrawal of tools), usually demands a filtrate considerably below 10 ml and sometimes as low as 1 to 2 ml. In addition to frequent requirement during the drilling of exploratory wells, muds with a filtration characteristic of 2 to 3 ml are in regular use for the drilling of the Dohuk shales in the Ain Zalah field, the formations between 8000 and 11,000 feet in the Zubair field, and the final section of wells in the Dukhan field.

Such filtration characteristics are achieved by modification of either

bentonite or salt-resistant clay muds with starch, which behaves satisfactorily under either non-saline or saline conditions.

Starch and Carboxymethylcellulose

Starch is at present the most satisfactory choice as a filtrate-reducing component for mud because of its favourable viscosity characteristic at concentrations required to produce low filtrates (see Figs 2 and 2 (*a*)). In this respect it is much superior to gum tragacanth, which also has a tendency to cause the development of rather stable foams. Only occasionally is foaming trouble experienced with a consignment of starch. It is always

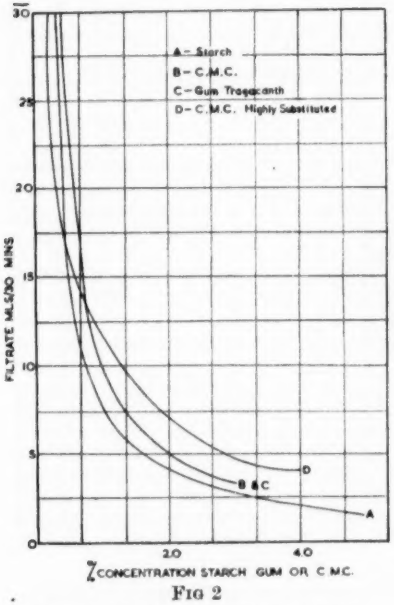

FIG 2

FILTRATES OF MUD TREATED WITH STARCH, GUM, AND C.M.C.

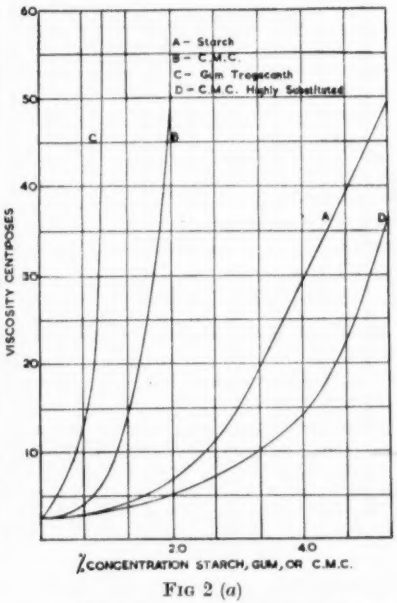

FIG 2 (*a*)

VISCOSITIES OF MUDS TREATED WITH STARCH, GUM, AND C.M.C.

used in the pre-gelatinized cold water dispersable form, which is so much more convenient than the preliminary heating or hydrolysis treatment required by unprocessed starch.

Filtrate reduction plotted against concentration does not give a straight-line relationship (see Fig 3). A mud with a high filtrate of 100 ml or one with a much lower filtrate of 25 ml, both require about $1\frac{1}{2}$ per cent of starch for reduction to 6 to 8 ml. Further reduction to 3 to 5 ml requires 3 per cent, and to 1 to 2 ml $4\frac{1}{2}$ to 6 per cent of starch. Furthermore, although some varieties of commercial starch are considerably more effective than others in low concentrations, quantities required to produce filtrates of 2 ml and less are not very dissimilar.

One of the disadvantages of starch-treated muds is their susceptibility to bacterial attack, the symptoms of which are an unpleasant odour and a

rapid rise of filtration characteristic. Three standard methods of protection are available :—

1. Advantage is taken of the immunizing effect of salinity, but to provide a reasonable factor of safety the salt concentration should be not less than 20 per cent (200,000 p.p.m.).

2. The use of pH control. For satisfactory protection the system should be maintained above pH 12. This is convenient when mud viscosity control involves the use of caustic soda or lime with tannin.

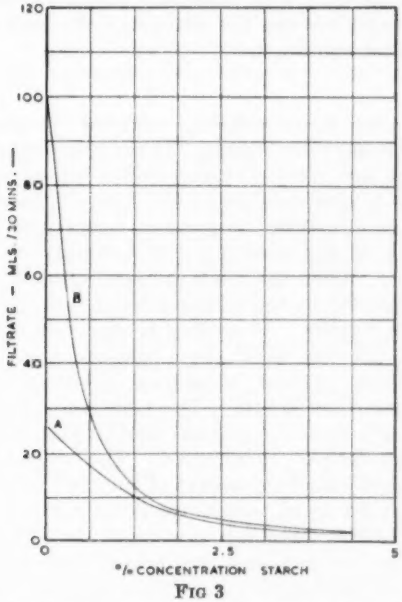

FIG 3

THE EFFECT ON FILTRATE OF STARCH ADDITION TO TWO DIFFERENT MUDS

3. The third method involves the addition of bactericides, and is used when salinity is too low to immunize against attack or when high pH conditions are undesirable. The preservative in general use is paraformaldehyde, but phenolic compounds such as sodium pentachlorphenate give quite as good a degree of protection.

The high-pH method is used extensively in the Zubair field and in the final section of the Dukhan wells, whilst the use of preservative is advantageously applied to the starch-conditioned section of the Ain Zalah wells, owing to the apparently adverse effect of high-pH mud on the already pronounced sloughing tendency of the Dohuk shales.

Carboxymethylcellulose (CMC) has been suggested repeatedly as a possible alternative to starch, and numerous samples have been examined. This substance fulfils the same major function as starch of reducing filtrate under saline and non-saline conditions, but the viscosity/filtrate relationship is

much less favourable. At concentrations required to produce filtrates of 2 to 3 ml the mud viscosity for most of the varieties of CMC examined is undesirably high, although this disadvantage appears to be reduced by the substitution of a proportionately larger number of carboxymethyl groups in the molecule (see Fig 2). Claims are also made that CMC is relatively immune to bacterial attack; this is quite appreciably slower, but protection is nevertheless necessary, and follows similar lines to the methods outlined for starch. Even on the basis of comparable flexibility of performance, which is approached only in the case of highly-substituted CMC, the very much higher cost of the latter still leaves starch with an overriding economic advantage, which must remain the decisive factor influencing choice of material under present conditions.

Lime-base Muds

Although bentonitic muds suitably modified by starch have many advantages, they also have limitations. In the case of untreated bentonitic muds, viscosity, gel, and filtrate characteristics are adversely affected by contamination with soluble calcium in the form of the sulphate resulting from the drilling of anhydrite or gypsum formations, the effect being considerable in view of the relatively low solubility of calcium sulphate (about 2000 p.p.m.). When the muds are treated with starch the filtrate is not appreciably affected by the soluble calcium, but the adverse influence on viscosity and gel persists. This effect is overcome by pre-treatment of the mud with hydrated lime, which, by a base-exchange reaction, converts the bentonite normally present as sodium montmorillonite to the less hydrated calcium montmorillonite. The new mud has rather lower viscosity and gel strength than the original, and its starch content maintains the filtration characteristic unimpaired. The conversion involves, in practice, a pronounced initial thickening of the mud while the effect of the lime in reducing the forces of mutual repulsion between particles of clay builds up to a maximum. The dehydration of the sodium base bentonite to the lesser hydrated calcium base type takes longer, but as this proceeds the resulting reduction in viscosity more than compensates for the primary increase and the mud thins to the new equilibrium point. It is essential, however, before the lime conversion to pre-treat the mud with appropriate quantities of caustic soda and quebracho, which have a moderating effect and without which thickening might be sufficient to render the mud uncontrollable. Lime-base muds are not only useful for the drilling of calcium-bearing formations but also permit the drilling-out of cement from casing without any of the special pre-treatment which has to be given to un-limed muds in order to offset undesirable changes of viscosity and gel which usually result therefrom.

Lime-base muds possess a further advantage associated with the drilling of deep wells, and this is of particular significance in the Zubair field, where the average completion depth of wells is 11,000 ft. The high temperatures which characterize the drilling of the lower sections of these wells gradually destroy the thixotropic properties of un-limed muds and lead to the development of irreversible gels. When " irreversible set " takes place the mud has no longer any response to the addition of controlling chemicals, and viscosity can be regulated only by dilution with new mud or with

water, to which must be added compensating quantities of starch for filtrate maintenance, and bentonite for maintenance of suspensive colloids. This use of material to compensate for dilution is uneconomical and only recommendable in the absence of a suitable alternative. Lime-base mud, which is affected to a lesser degree than the normal bentonitic mud, provides such an alternative, and not only enables drilling operations to proceed more smoothly, but also requires considerably less maintenance than an un-limed mud over the difficult period associated with the continuous coring of the last several hundred feet of formation and long exposure under static conditions to the high-temperature effect of deep hole conditions.

Elsewhere, lime-base muds are used effectively in the deeper portion of the Dukhan wells, which is characterized by a steep temperature gradient and beds of anhydrite separating the oil-bearing limestones.

Emulsion Muds

Oil-base muds have not yet been used in the Iraq Petroleum Company's fields, but the use of emulsion muds, which incorporate oil as an essential component of the liquid phase, is now firmly established. The preparation of this type of mud involves the emulsification of diesel or crude oil in a bentonite/water mud. This is facilitated by pre-treatment with caustic soda and quebracho, which also assists in the control of viscosity. The quantity of oil used varies from 10 to 15 per cent. Emulsion muds have a higher than average viscosity (55 to 70 Marsh seconds), but this is not disadvantageous, as the gel is no higher than the normal working characteristic for non-emulsified muds. Filtrates average 5 to 6 ml, and therefore the muds require proportionately less starch to reduce to the 2- to 3-ml level when this is required. Economy in starch is, indeed, one of the very recommendable features of these muds. When it is realized that starch represents about 30 per cent of the total cost of mud materials consumed in these areas since the beginning of the post-war programme, the saving due to economy of this material may be exemplified by a comparison of starch consumption figures in the Zubair field during the months May to October 1950, when no emulsion mud was used, and the corresponding six months of 1951, when emulsion muds were in regular use :—

4-string programme, May–October 1950, 110 tons.
4-string programme, May–October 1951, 52 tons.

Although the behaviour of these muds is generally very satisfactory, they are liable to some of the defects common to bentonitic muds, notably the effects of soluble calcium salts and of high temperature. The former give no trouble in Zubair, as the only significant anhydrite is penetrated while drilling the first 2000 ft before introduction of emulsion mud, but from 10,000 ft high temperatures give rise to high gels and irreversible set. This difficulty is much reduced by lime treatment, as in the case of conventional bentonite/starch muds.

Emulsion muds are also being used successfully in the Dukhan field for the drilling of sloughing shales and porous limestone formations. The mud is lime-treated after setting $9\frac{5}{8}$-inch casing and well in advance of the anhydrite encountered in the last thousand feet. Emulsion mud is also

now being used advantageously for the drilling of exploratory wells in the Kirkuk area.

The satisfactory performance of these muds under non-saline conditions is stimulating efforts to develop saline emulsion muds. These might be of special interest in the Trucial Coast area, where no adequate source of fresh water has been located. The usual emulsifiers, such as caustic soda, are ineffective under saline conditions, but laboratory experiments confirm that stable emulsion muds with suitable characteristics can be produced with the aid of the calcium salts of lignin–sulphonic acids. Unfortunately, however, copious and persistent foams are developed in these experiments. This seriously affects weight and pump pressure, and constitutes a major obstacle to the use of such muds in the field. Dispersion in a colloid mill may intensify foam production to a greater degree than mixing under field conditions, especially where air-cutting is substantially reduced by keeping the nozzles of the mud guns submerged beneath the surface of the mud during agitation, but attempts to simulate these conditions as nearly as possible in the laboratory still promote copious stable foams. Noticeable improvement results from the addition of small quantities of antifoam reagents such as octyl alcohols and trimethylhexanol, but it is not nearly enough to justify large scale application within the economically practical limits of these materials; in view of this, field trials must be deferred until this difficulty can be more satisfactorily overcome.

Salt Water

A special development which is applied with conspicuous success when conditions are favourable is the use of salt water in place of dispersed solids. The use of salt water avoids mud ringing, and where the hydrostatic pressure is sufficient to control any gas encountered offers the maximum assistance to the escape of entrained bubbles, which in viscous muds cause the progressive lightening that precedes a blow-out. During the drilling of salt beds the pre-saturated fluid prevents enlargement of hole, and no troubles arise from the drilling of anhydrite or gypsum.

The specific gravity of saturated brine is nearly 1·2, and weight builds up rapidly to at least 80 lb/cu. ft. by the dispersion of finely ground material from formations drilled. Such a fluid removes cuttings adequately so long as a sufficiently high velocity of circulation is maintained. Precautions should, of course, be taken to circulate the hole free from cuttings before shutting off the pumps prior to withdrawing tools. If a stage is reached where removal of cuttings becomes difficult, salt-resistant clay is added in minimal quantities compatible with requirements. The advantage of the use of salt water under favourable conditions is clearly demonstrated by the example of a well in Syria drilled to a depth of 9461 ft. In this case salt water was used without any addition as far as 7500 ft, and the remaining footage was completed with the addition of some 4 tons of salt-resistant clay. Advantage is now taken of this method for the drilling of the first 1600 ft of the Dukhan wells, with considerable saving of clay. Conditions are often unsuitable, however, for the employment of this method. It is not adaptable when sloughing formation is encountered, and an attempt to use it during the drilling of a recent Trucial Coast well was rendered unsuccessful on this account. Neither is it suitable for drilling unconsolidated

formation. When applicable, however, it is very economical, as may be seen by reference to Table IV, which compares the cost of the Syrian well cited with other exploratory deep wells.

Maintenance and Control of Muds

The successful maintenance of desirable characteristics, whatever the mud system in use, requires as first essentials :—

(1) Regular checking and recording of weight, viscosity, gel, filtrate, and, when relevant, pH and salinity.

(2) Pilot-testing with controlling chemicals, which determines—

(*a*) selection of the most suitable material when alternatives are applicable; and

(*b*) addition of optimum quantities to ensure that modification proceeds in the direction and to the degree desired.

When a mud has been adjusted to desirable weight, viscosity, gel, and filtrate characteristics for a given set of conditions, it usually happens that after a short time one of these gets out of balance without appreciable alteration of the others. The correction of any one characteristic, however, may and probably does affect the others; for example, dilution of the mud to reduce weight affects viscosity and filtrate simultaneously. It is important, therefore, to supply compensating corrections for the remaining characteristics when adjusting any particular one of them. Optimum mud conditions also vary considerably with changing subsurface conditions. Weight is adjusted to control pressures adequately and, where possible, to assist filtrate reducers in minimizing fluid losses to porous formation with the development of a correspondingly thick wall cake. Viscosity is reduced to the minimum compatible with adequate suspension when gas is present, and raised as much as smooth operating conditions permit when drilling sloughing formation. The high filtrate of a saturated brine with no clay solids is appropriate for the drilling of anhydrite formation, whilst sloughing shale like the Dohuk beds of the Ain Zalah field requires reduction to less than 3 ml.

Weight and Filtrate Control

The actual application of weight and filtrate control is relatively straightforward. The former involves appropriate additions of barytes to increase or water to lighten, as required, with any necessary compensation for filtrate and viscosity changes introduced by these operations. Filtrate adjustment similarly involves additions of starch commensurate with the reduction required, together with any weight and viscosity compensation when the starch is dispersed in water prior to stringing into the system.

Viscosity Control

Control of viscosity is rather more complex, as it introduces selection of different types of controlling chemical and is also associated with considerations of pH value. Chemical control of viscosity, moreover, is concerned only with structural viscosity of gel formation. Any viscosity due

to the packing effect of solids in high concentration is controllable only by alteration of the solid/liquid phase relationship. Neither does chemical control directly affect viscosity due to hydration of bentonite. Materials used for viscosity control fall into three main groups, of which representatives from each of the first two are always used together :—

(a) *Alkalis*

Soda ash (Sodium carbonate)
Caustic soda (Sodium hydroxide)
Lime (Calcium hydroxide)

Used alone, caustic soda and lime cause uncontrollable thickening, and for thinning purposes are always used with a tannin compound like quebracho. These materials function primarily through their influence on pH adjustment. Soda ash influences viscosity also through elimination of soluble calcium; lime exerts an indirect influence on viscosity due to hydration by conversion of sodium to calcium montmorillonite, and prevents further adverse influence of soluble calcium sulphate.

(b) *The Tannins*

Quebracho is the most generally used variety. Tannin compounds are not very soluble and have a low pH (usually about pH 6); they are dispersed with the aid of caustic soda, forming soluble sodium tannate. The effect on viscosity varies according to the ratio of caustic soda to tannin, a 1 : 1 ratio being most frequently employed. Fig 4 illustrates the effect of increasing concentration of three ratios of caustic soda/quebracho on a typical bentonitic mud and indicates the importance of pilot tests prior to treating the system to determine optimum concentration and avoid over treatment.

(c) *The More Complex Phosphates*

Three of these are employed in the operations described :—

	pH value of 10% concentration in fresh water
Sodium acid pyrophosphate $Na_2H_2P_2O_7$ . .	4·2
Sodium metaphosphate glass $(NaPO_3)_n$ . .	6·0
Tetrasodium pyrophosphate $Na_4P_2O_7$ . .	9·7

All these mud-thinners, or more correctly gel retarders, are effective only under relatively non-saline conditions, their use being generally limited to salinities below 10,000 p.p.m. The phosphates are also adversely affected by high-temperature conditions, as they revert, under the influence of heat, to sodium orthophosphate (Na_3PO_4), which has a flocculating effect on the mud. For this reason they are not used in deep hole drilling. Apart from their viscosity reducing properties, the alkaline tannates assist in limited reduction of filtrate. The phosphates do not influence filtrate in the way.

The alkaline tannates are used for the normal preparation and control of

bentonitic and emulsion type muds. They are used for the additional purpose of maintaining a high pH system when this method is selected for protection of starch. They are similarly used, together with lime, for the preparation and protection of lime-base muds.

In drilling operations caustic soda with quebracho is most generally used for viscosity and gel control during the penetration of limestones and marls, and together with lime in deep hole, irrespective of formation conditions, owing to the adverse effect of high temperature on phosphates. The latter, however, are more effective for the drilling of certain types of shale, particularly those which disperse rapidly in the mud. The rate of dispersion of

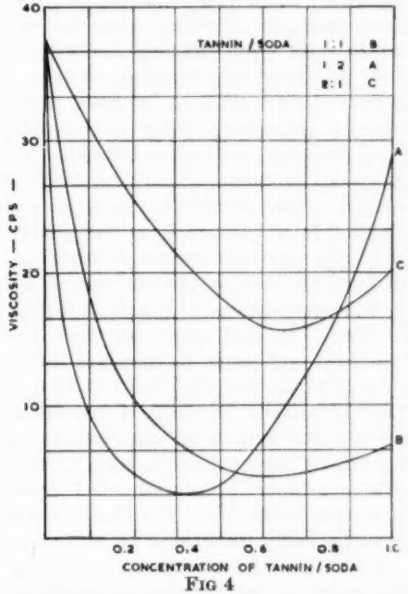

FIG 4

EFFECT ON MUD VISCOSITY OF ALTERING THE RATIO OF TANNIN TO SODA

shale increases as pH increases, and is therefore appreciably slowed down by metaphosphate and still further by acid pyrophosphate treatment. Phosphate treatment is being most generally applied to the Khatiyah shale section of the Dukhan wells and for the loose sandy formations in the first 2500 ft of the Zubair wells.

Soda ash finds a very limited use as an eliminator of soluble calcium in the drilling of formations containing thin layers of anhydrite, when it is not considered economical to convert to a lime-base mud; when applied it is used with quebracho. Limited use is also made of barium carbonate for the same purpose; but these materials are used on a very small scale compared with the more flexible and more easily maintained lime-base muds.

Loss of Circulation

Although considerable thicknesses of limestone are drilled without any serious difficulty, troubles frequently occur when the formations are

characterized by high porosity or fissures. The former case involves water loss and the build-up of mud cake on the wall of the hole. This is usually satisfactorily overcome by the use of low filtrate mud, assisted to some degree by appropriate increase of viscosity and gel and where possible by reduction of weight. Fissured limestone, however, involves total loss of mud irrespective of its characteristics. The rate of loss varies with the size of the crack and the excess pressure of the mud column, but mud solids are of such fine dimensions that a 1-mm fissure can lead to the comparatively rapid loss of a large volume of mud. In the case of fine cracks some measure of relief may be gained by reducing the weight of the mud column, and increasing viscosity. In general, however, mud losses of this kind are treated by one of two methods. Attempts are first made to form a bridge in the crack on which mud may build up and establish a seal. Various materials are used for this purpose. Some are of local origin such as cotton-seed hulls and sawdust; others, such as chopped sugar cane and shredded cellophane have to be imported. They are broadly differentiated by varying degree of compressibility, swelling tendency, shape, and dimensions of their component units. With comparatively bulky material of this kind concentration is limited by pumpability through the watercourses of the bit. Efficiency is unpredictable and depends on the nature of the fractures in question. It is not infrequent to reduce a mud loss of 50 brl an hour (1750 gals) to 1 or 2 brl an hour or even to zero in a comparatively short time. Sometimes, however, the rate of loss is much higher, and sealing agents have little effect. In such cases recourse is had to cementation. It is usual when cementing fissures to increase the gel properties of the cement slurry by the admixture of relatively small quantities of bentonite. The slurry thus treated rapidly develops a resistance to flow within the fissure and establishes a seal with minimum loss of cement.

Losses of this kind are a very expensive form of mud trouble. Much of the loss is inevitable and occurs before remedial measures can be applied. The extent to which such losses affect the total mud requirements for the drilling of wells is realistically illustrated by the case of the Zubair field, where two zones of fractured formation are regularly encountered. For wells in which fracturing is less pronounced and mud loss more easily checked, the total requirement for the 11,000 ft drilled amounts to 10,000 to 11,000 brl, while for wells in which greater difficulty is experienced, the volume of mud required is as much as 20,000 to 22,000 brl. A still more striking example is that of a recent test well drilled in the Kirkuk area, where the volume of mud used over a section of hole 3500 ft thick amounted to 21,000 brl. In contrast may be cited the case of 10,000-ft wells characterized by the absence of fracturing, with a total mud requirement of 6000 brl.

The Economic Aspect of Mud Control

The cost of mud control is primarily determined by the nature of formations drilled—their composition, texture, porosity, freedom from fracturing, and other properties—the presence of water or gas, and also the depth of penetration which introduces the effect of temperature. These considerations determine the type of mud and the mud characteristics most appropriate for the subsurface conditions encountered. A brief summary of

mud practice in three different fields is appended, and Table I, which gives average mud characteristics in use during 1951 in these fields, illustrates the effect on choice of mud characteristics of the varying formation conditions and depth. The muds and characteristics used for exploratory wells are, of course, much less specific, and because of unpredictable factors, the cost of materials is much higher. Table II gives some idea of the very wide variation in the cost of mud used for drilling a number of deep

TABLE I

Average Mud Characteristics for wells in the Zubair, Dukhan, and Ain-Zalah fields (1951)

	Typical thicknesses, ft	Weight, lb/cu. ft.	Viscosity, Marsh sec	Filtrate, ml
Zubair				
Upper sands and limestone	2000	72–73	36–38	high
Bahrain limestone	500	73	38	15
Rus anhydrite	500	73	45	35
Upper Cretaceous shales and limestone	4000	73	45	10
Khatiyah shales	1500	76	55–60	3
Mauddud limestone	500	78	50–55	12–18
Nahr Umr shale and limestone	1000	79	50–55	8
Zubair shale and sandstone	1000	80	50–55	2–3
Dukhan				
Bahrain limestone	1100	70	30	high
Aruma shale and limestone	900	76	31	,,
Khatiyah shale and marl	900	75–80	35	10–15
Mauddud limestone	200	77–80	35	5–6
Nahr Umr sands	500	80–82	40	4–6
Thamama limestone, shale, and marl	2000	79	38	4
Riyadh Group—limestone and anhydrite	1000	78–80	36–38	3
Ain Zalah				
Lower Fars limestones, gypsum, and anhydrite	500	76–78	33–40	45–65
Djeribe and Sinjar limestone	2500	76–80	35–40	50–60
Dohuk shales	2000	77–80	46–70	2–3
Ain Zalah limestone	2000	70–75	35–50	8–12
Formations below Ain Zalah limestone in deeper wells	3000 +	71–73	35–50	2–6

exploratory wells, and Table III contrasts the cost of the exploratory phase with that of later wells drilled in the same area in the light of experience with subsurface conditions and modification of the types of mud employed.

Whilst the type of mud and general lines of control determine the actual class of components and controlling chemicals, selection of the most advantageous commercial representatives of each class is made by careful comparison of behaviour under standardized conditions in the laboratory. In the field a balanced efficiency/economy relationship is maintained by means of regular checking of characteristics and the pilot testing so indispensable to their satisfactory adjustment. Major changes in policy are

generally made in accordance with changing world trends in mud development, where these are applicable to local conditions. Modifications of established methods are based on the conclusions drawn from laboratory

TABLE II

Variation in the Cost of Mud Materials Used for the Drilling of Deep Exploratory Wells in Different Areas

	Depth, ft	Cost of mud, £
Southern Iraq	12,692	37,900
	11,171	16,549
	8,363	16,352
Trucial Coast	13,001	21,903
Syria	8,594	11,300
	10,163	7,088
	10,250	3,416
	9,461	572 *
Lebanon	10,059	1,664

* Drilled almost entirely with saturated brine.

experimentation closely linked with field observation and experience. Reference to Table IV gives an idea of the relative consumption of the various types of mud material, some in constant, others in less regular use, but all important in their own special sphere of influence.

TABLE III

The Comparative Cost of Mud Materials Used for Drilling Wells in Different Areas, Showing the Influence of Progressive Mud Development and Control in Two of these Areas

		Average cost, £
	Zubair field (Average depth of wells 11,000 ft)	
1948	Exploratory wells	16,000–18,000
1949–50	Earlier development	10,000–13,000 *
1951–52	More recent development	5,000– 9,000 *
	Dukhan field (Depth of wells 6000 to 7000 ft)	
1947–49	Earlier wells (Saline water period)	5,000– 8,000
1951	Development in fresh water period	3,000– 3,000
1952	Recent modification	1,200– 1,500
	Ain Zalah field	
	Wells drilled to 5,000–5,500 ft	1,200– 1,600
	Wells drilled to 9,000–10,000 ft	9,000–10,000

* Variation due to mud losses.

This table also compares the quantities of material consumed on a basis relative to the total cost and emphasizes the relatively high cost of starch as compared with the quantity used. A similar observation applies to starch preservative. The economic advantage of emulsic . muds, which use proportionately less starch to produce low filtrate characteristics, and

still more that of the lime-emulsion muds, which dispense with preservative, may readily be appreciated, and stress the importance of mud development trends. A more unfavourable feature which emphasizes factors of a less controllable and often unpredictable nature is illustrated by the note on consumption of barytes. Fractured formation or gas can distort an otherwise soundly planned mud economy, and in comparing mud material costs

TABLE IV

Comparison of the Relative Percentage Quantities and Cost of Mud Materials Used in the Fields of the Iraq Petroleum and Associated Companies (1947–51)

	Per cent Weight	Per cent Cost
Barytes	57·3	27·6
Bentonite	26·7	19·1
Starch	7·0	30·5
Salt-resistant clay	4·1	4·3
Quebracho	1·3	6·8
Caustic soda	1·2	1·8
Lime	1·1	0·7
Phosphates	0·55	2·7
Starch preservative	0·35	5·1
Sealing agents	0·25	1·2
Soda ash	0·15	0·2
	100·00	100·00

Note : The influence of gas and mud losses in fractured formation on consumption is illustrated by the fact that 45 per cent of all the barytes used may be allocated to comparatively limited sections of seven exploratory wells.

in different areas it is very important to take into consideration variations in local conditions and the relative absence of drilling troubles.

In conclusion, it may be said that economy in mud control is not a question of price only, but the price/efficiency relationship under given conditions, in which mud costs represent the premium paid on insurance against related troubles.

ACKNOWLEDGMENT

Acknowledgment is due to the Iraq Petroleum Co. Ltd. for permission to use information included in this paper.

APPENDIX

SUMMARY OF MUD PRACTICE IN USE IN THE ZUBAIR, DUKHAN, AND AIN ZALAH FIELDS DURING 1951

Zubair field

The upper sandy formations are drilled with a bentonitic mud which has to be continuously diluted to prevent building up of weight. After setting 16-inch casing (800 to 900 ft) a similar mud is used, with phosphate control for viscosity. The heavy mud losses which occur at about 2300 ft are usually controlled with cottonseed hulls and sawdust. This zone is shut off by 11¾-inch casing set about 2500 ft, and the mud, after treatment with caustic soda and quebracho, is converted to an oil emulsion. This emulsion mud is used for the remainder of the well, starch being added to adjust filtrate as and when required. Heavy mud losses occur between 5600 and 5800 ft. These are controlled with cottonseed hulls and sawdust or chopped cellophane where possible, or in acute cases by cementation. Viscosity is controlled with caustic soda and quebracho to about 9500 ft, where the mud is suitably treated with lime to reduce gel troubles caused by high temperature.

Dukhan field

A salt-resistant clay/saline water mud is used until circulation is lost (200 to 300 ft), and from this point drilling is continued with water alone. The salt water is used to about 1800 ft, where the system is changed to a bentonite/fresh water mud. Viscosity and gel are controlled by phosphates, and filtrate reduced by starch as required. Before reaching the Nahr Umr sands, weight is allowed to rise to a minimum of 78 lb/cu. ft., which is critical for the control of a flow of saline water. After setting 9⅝-inch casing (4000 to 4500 ft) the mud is lime-treated. Filtrate is maintained with starch at 3 to 5 ml for the remainder of the well, and a viscosity of 35 to 40 Marsh seconds with caustic soda, lime, and quebracho.

Note : Since the beginning of 1952 it has become the practice to use oil emulsion mud from about 1800 ft. Control treatment of filtrate with starch, and of viscosity with phosphates as far as the 9⅝-inch casing, and thereafter with lime, caustic soda, and quebracho remains unchanged except that proportionately less starch is required.

Ain Zalah field

A low concentration of bentonite is used to improve mud made from local shale for drilling the upper limestone formations. Little attention is paid to filtrate, and any gel trouble caused by anhydrite is controlled with soda ash and quebracho. When approaching the Dohuk shales, filtrate is appropriately reduced with starch, and while drilling this formation is maintained at 2 to 3 ml. Viscosity is likewise kept as far as possible between 50 and 70 Marsh seconds, using quebracho or phosphates to control within these limits. Protection of starch from fermentation is ensured by addition of paraformaldehyde. After casing off the Dohuk shales a bentonite mud without starch treatment is used for the completion of wells in the Ain Zalah limestone. For deeper wells, however, the mud is starch-treated to maintain filtrates of 2 to 6 ml. Caustic soda and quebracho are used for viscosity control. The mud is lime-treated before reaching the anhydrite beds of the Jurassic.

Note : Where possible, the upper limestones are now drilled with water alone to within a short distance of the upper Dohuk shale.

Units of Reference

Since the conclusions drawn from small scale laboratory experiments have to be applied to very much larger quantities of material in field practice, it is sometimes convenient to work in different units. In the field mud volumes are measured in barrels, and weight of materials in pounds and tons. Volumes and weights on the laboratory scale are expressed in millilitres and grammes.

Mud characteristics referred to and regularly tested involve weight, viscosity, gel, or shear strength, filtrate, salinity, and pH.

Mud weight is measured by means of a mud balance, whether in the laboratory or the field, and is expressed in pounds per cubic foot.

Viscosity is measured in the laboratory by means of a Stormer viscometer at 600 revolutions per minute and recorded in centipoises. Viscosity in the field is more conveniently measured by a Marsh funnel viscometer. The basis of the test is the time in seconds taken for the efflux of 1 quart (946 ml) of mud from a standard funnel containing 1500 ml.

Gel strength measured by a Stormer viscometer is expressed in grammes or by a shearometer in lb/100 sq. ft.

Filtrates are always recorded in millilitres representing the volume of fluid from a 30-minute test at 100 p.s.i. in a 7-cm standard pressure filter.

Salinity is determined by titration with standardized silver nitrate, the chlorinity thus measured being calculated as sodium chloride and expressed in parts per million.

pH is measured by means of pH meter. Alkalinity is sometimes measured as an alternative to pH by titration with standardized acid, and is expressed in parts per million.

Discussion

E. Cooper Scott : Mr Paxton has approached his problems in a very common-sense manner, and has told us what are his difficulties and his objectives, and how he makes his mud. It seems that he has not any favourites, as have many mud engineers; some are apt to favour one particular mud and one particular additive.

Mr Paxton's experience stretches over a wide range of conditions. We all know how important good mud is for every drilling operation in the world, but our problems are not always the same. If point were needed to my contention, it is afforded in a statement I noticed recently in a trade journal which stressed the importance of good circulation. It was stated that, even with good mud of low viscosity, only 15 per cent of useful work is accomplished by the average slush pump, due to pressure losses in the drill stem. Furthermore, the absolute statement was made that it requires twice the energy to push a given volume of mud through a 2-inch drill stem or collar as through a 2¼-inch one. All this is rather approaching the thing from the other end, and I am rather doubtful about it, but the alternative to good mud is plenty of friction loss in the pipe.

In his paper Mr Paxton emphasizes two main objectives which in his case transcend all others, namely, to overcome trouble in connexion with mud ringing on porous strata, and loss of circulation into macro-porous strata. My experience in this connexion has been so different from his that I find it somewhat difficult to raise points for discussion, because his is the territory of open sea geology—limestones, calcareous shales, anhydrite silts—whereas in Trinidad I have been concerned with deltaic conditions of shale, sand, and silt, compressed and contorted, and these call for very different handling. Thus, my remarks must rather take the form of posing a few questions and indicating the differences throughout the world.

It was in Trinidad that I first had experience of mud control. While drilling one of the first rotary-drilled wells, it blew out; some mud was put in and it still blew out. There was no telephone available, and I wrote a "polite" letter to the Manager. He wrote back stating that he understood hæmatite was a good thing, and he sent me, via the coast, 100 lb of hæmatite, stating that it was necessary to weigh it carefully, for otherwise it might become too thick! We used all the hæmatite, but of course we did not get very far with it.

In Trinidad the mud normally used weighs from 100 to 130 lb/cu. ft., and is a water-based mud; that is because the pressure gradient is, roughly, 0·7 lb/ft. I would ask Mr Paxton what is the pressure gradient in his territory, because high pressures lead to many problems. We find that, quite apart from the necessity to hold down the gas and fluid which comes into the hole at 0·7 lb/ft, another factor which makes it necessary to use mud slightly heavier than our pressure gradient is definite evidence that at below about 8000 ft the weight of the overlying strata, especially in the basin, tends to be greater than the structural strength of the shales, and there is a certain amount of spalling and rock bursting. For a long time the mud engineers discounted the possibility of this, and said that it was simple hydration, which made the clay come into the hole and which should be avoided with a low water-loss mud.

Recently we went over to oil-base mud, and my Company uses it now 100 per cent. Incidentally, this has confirmed the crushing of shale. We have been producing from 12,000 ft, where there is a shale band right in the middle of an oil sand, and nothing that we could do by holding by beaning the pressure of the oil and gas, which was, I think, 0·6 lb/ft, would prevent the shale spalling.

I should like to ask whether Mr Paxton has considered using oil-base

mud. We have found that as a general purpose mud it is the best. It is expensive in the first place—I think it costs us about £3 per barrel to make —but it is long lived. There is no contamination from the formation and, provided you have the means of transport from well to well, the only loss is that involved in the coating of the cuttings coming off the screen. It is amenable to treatment for loss of circulation, and it is very good for temperature control. When we use it in connexion with a bottom hole temperature of 190° F it is perfectly stable.

Adverse factors are that bit penetration in hard iron-cemented sand is poor as compared with water-base mud; it is necessary to use a special form of induction electric logging because it is non-conductive, but it gives an uncontaminated and undissolved sample from cuttings, which look just like lathe cuttings. Also it is believed that, to some extent at any rate, it does improve the oil flow rates in our dirty deltaic oil sands, which are clay contaminated. It prevents base exchange of such clay particles, as does Mr Paxton's emulsion mud, and both stop the swelling of shale particles in the sand by water contamination.

With regard to the costs given in the paper, I note that the costs of materials only are recorded, and I wonder how much technical control will add. Is there a chemist on each well now, and is it necessary to work them in shifts, because that would add considerably to the cost? Once the oil-base mud is stabilized, a great deal of control is not necessary.

I am astounded by Mr Paxton's starch cost. Our clays, unlike his, are colloidal, and they go on making the water-base mud more viscous; eventually we have to thin it down and add more barytes in order to maintain weight with good viscosity.

I should like to say how interested I was in the thickening of his lime–starch muds when caustic soda and quebracho were added. We used starch mud in a particular well in Trinidad, and we experienced just that trouble of the mud thickening up immediately after the addition, and I wonder now whether, if we had persisted, we might have got it to work.

I should like to ask Mr Paxton whether he has any experience of loss of circulation due to too much pump pressure, such as pumping against closed well-head valves, which does not occur unless too much pressure is applied to the hole—in other words, whether he has had any indication of formation fracturing. We have experienced formation fracturing at 12,000 ft simply through running out the hole too fast, and this has resulted in starting loss of circulation, which has continued until we put in something to seal the cracks. It may be that his mud weights are too low to bring that about.

Finally, what is " Attapulgite," and from where is it obtained?

MR PAXTON : I doubt whether twice as much power is required to pass a given volume of mud through a 2-inch bore as through a 2¼-inch bore.

As regards pressure gradient, that may vary in different fields, but on only three or four occasions have we had to use mud heavier than 100 lb/cu. ft.; usually the conditions have not called for a mud heavier than 85 to 90 lb.

Concerning loss of circulation due to too much pressure, I think there

have been one or two instances of failure which might have been attributed to that. However, I am not absolutely certain about it.

Attapulgite in its crystalline form, as shown by electron micrographs, is very different from that of montmorillonite. The Attapulgite particles are definitely in the form of needles, which possibly accounts for the poor filtration properties of muds made from it.

MR COOPER SCOTT : I was interested in its occurrence in nature.

MR PAXTON : I think it occurs principally in Florida and Georgia, and it is sold under the names of Zeogel or Attaso. I have heard recently of a possible source in Nigeria, but how much of it is there I do not know.

R. K. SMITH : You have mentioned that bentonite is normally used with fresh water, whereas Zeogel should be used with salt water. Up to what concentration of salt can you use bentonite ?

MR PAXTON : In normal circumstances when the concentration of salt exceeds about 1 per cent, the use of bentonite is unfavourable. Certainly there should not be more than 1 to 2 per cent of salt.

MR SMITH : That would be about 20,000 parts per million.

MR PAXTON : Yes, in a general way I should regard this as the upper limit for using bentonite advantageously.

MR SMITH : When you found it successful to use salt water with a specific gravity of 1·2, I take it that was due to the fact that you had not a high pressure formation; otherwise you would have been up all night.

MR PAXTON : Yes, of course. It is useful only where the pressure can be controlled. When dealing with a high pressure formation weighting material must be added, and means of suspending any added weighting material must be provided.

MR SMITH : Although you said that you drilled mainly through limestones or calcareous shales, you had some sand. From the point of view of the ultimate productivity of those sands, have you not been afraid of water blocking, and have you thought of using oil-base mud ?

MR PAXTON : So far it has not been considered that the productivity has been very adversely affected by the types of mud used.

DR T. WHITE : I should like first to ask whether it is correct to say that in converting a mud to the lime-based type it is essential to have tannin and alkali present before the addition of lime, otherwise the lime treatment causes flocculation, which cannot be broken over to a properly dispersed condition. In other words, if tannins are not present initially the addition of lime is not followed by a proper break-over.

MR PAXTON : This is correct. It is absolutely necessary to have tannin and caustic soda present before the lime is added, otherwise an uncontrollable thickening develops.

DR WHITE : Thank you. A further point which puzzles me is that when an ordinary mud is treated with alkali and quebracho the viscosity and the water loss are normally reduced. It is generally assumed that this is due to dispersion of the mud particles, the formation of the smaller particles reducing friction and therefore reducing viscosity, while the closer packing possible with smaller particles also cuts down the filtration rate or water loss. That seems a logical explanation.

In the case of the red lime muds, however, the presence of tannin reduces the viscosity due to the dispersal of the calcium bentonite, but this formation of smaller particles is not accompanied by a fall in water loss, although presumably it could allow of closer packing. This suggests that the basic theory of the viscosity and water loss relationship holds for the one group of muds but not for the other, and I would be grateful if Mr Paxton could throw any light on this.

MR PAXTON : I do not think I can answer that question to your satisfaction. There are so many apparent anomalies arising from this work, and much repetition of experiments is necessary before we can draw conclusions. I would hesitate to draw any conclusions in relation to these particular circumstances.

A. FRANK DABELL : Mr Cooper Scott reasonably asks whether or not a chemist was needed behind the driller. In the past we have had the geologist there, and I think a chemist would be necessary to implement the projects that are put before us.

I would ask Mr Paxton if there is yet a standard viscometer which will enable a man in Iraq, for instance, to compare notes with a man in the United States in connexion with drilling muds ?

MR. PAXTON : There are two instruments in general, but not universal, use, the Marsh Funnel and the Stormer viscometers. In the not distant future we may see a universal viscometer.

MR DABELL : When you speak of salt water, do you mean seawater ?

MR PAXTON : Not necessarily. You may have a formation water of a much higher salinity than that of seawater.

MR DABELL : I am very much concerned about the implementation of the results that have been obtained. The information which has been put forward in the paper might not be comprehensible to the average driller. Whilst it comprises very useful data to have in the office, will it really advance economic commercial drilling ?

MR PAXTON : It is largely a question of the responsibility of the petroleum engineering departments.

CHARLES DABELL : May I ask Mr Paxton whether he has encountered hot sulphurous water during drilling, and, if so, what effect it has had on the mud ?

MR PAXTON : I do not think we have encountered sulphurous waters at high temperature, but a sulphurous water has been encountered in one well in the Basrah area ; it was not at very considerable depth, so that it was relatively unaffected by temperature. It caused a certain amount of difficulty with the mud temporarily ; but these troubles were largely overcome when a lime-based mud was introduced.

E. DUX : We have learned that starch is an excellent material to add to a drilling mud, and also that its use adds to the operative costs of drilling. Starch solutions are strongly thixotropic, and I should like to ask whether a measure of variation in the viscosity and thereby possibly in the filtration rate can be achieved by altering the rate of flow of a starch-containing mud. If the rate of flow is increased the viscosity should decrease.

MR PAXTON : I do not think that matter has been studied particularly, or at any rate in connexion with IPC Fields.

Mr DUX : From the purely chemical point of view it can be shown that strong alkalis, particularly caustic soda, of pH higher than 10 have a strong hydrolytic effect on the molecule of starch. From the theoretical point of view I would suggest that it would be better to use starch of a low pH, say about 8, thus maintaining a higher molecular weight, and thereby improving the properties.

MR PAXTON : So far as I am aware there are no specific data on the matter, but I do not know that there is any great influence on the characteristics.

H. C. LACK : I should like to put some questions on behalf of my colleague, J. R. Gregath, which are based on his experience in the Persian Gulf area.

First, has Mr. Paxton had any experience with North African bentonites of extremely high yield ?

MR PAXTON : We do use a lot of bentonite from North Africa, and it has been satisfactory. I think also that the operators in the Persian Gulf express the same view with regard to it.

MR LACK : Do you think, when using an extremely high yield clay, that the sometime attendant high gel properties could be better controlled by converting the mud to " lime-base " ?

MR PAXTON : Yes, definitely.

MR LACK : Has the IPC any experience with " gum ghatti " in place of starch in a lime-base mud ?

MR PAXTON : I have no experience with gum ghatti; during the war we did much laboratory work with gums, and I have worked in the laboratory on various types, but not with gum ghatti. The foaming tendency of gums is very pronounced, especially gum tragacanth, and it is a very serious obstacle. I think that, although gums have good filtrate properties, the filtrate/viscosity relationship compares unfavourably with the starches. That goes for tragacanth and karaya, and in my experience for gums in general.

MR LACK : It will become air cut ?

MR PAXTON : Yes; or under appropriate circumstances, gas cut. If there is severe air cutting considerable corrosion of the drill pipe is likely to occur.

MR. LACK : The final question refers to Fig 4, where viscosity is plotted against the concentration of tannin/soda. Are references available for the construction of the curves in Fig 4 ? We find these curves interesting, as we are using a tannin/soda treatment on some of our muds in Kuwait.

I think the background to the question is that our engineers have been using what they thought was a good composition, which corresponded to the " C " additive.

Mr Gregath is now surprised to see from Fig 4 that it does not appear to be as effective in reducing mud viscosity as additives with a lower tannin/soda ratio, and he would like to ask whether the figure is based on information given by makers of some proprietary composition or is the result of your own experiments.

MR PAXTON : They are based on figures obtained when using these materials with one particular clay; you will not get the same results if you use them over a whole range of clays, and the curves will vary very considerably. I have given the curves as being typical and to illustrate the differences which do occur when using different ratios of tannin to caustic soda.

E. C. MASTERSON : In listening to Mr Paxton's most interesting paper, it was evident that he was very cost-conscious and that in his work never lost sight of the cost factor. In this connexion I was most impressed by the very high figures of mud losses mentioned. Mud, in the oilfield sense, is an expensive product, and these high losses must have cost a lot of money. In Kuwait, where conditions permit, we do not normally delay drilling operations until complete returns are obtained. In fact, large sections of the hole are usually drilled with no returns. Quite recently we drilled about 2800 feet in one hole without any returns whatsoever. Drilling proceeds with the pump delivering the maximum quantity of water which can be made available. The cuttings enter the zone of lost circulation and eventually seal these off. If not, casing is eventually run in and cemented, the cement rising in the annular space up to the zone of lost circulation. The annular space is then cemented from the surface.

I should like to ask Mr Paxton a question regarding the use of salt water

for drilling. Do you not experience trouble with enlarged holes or the twisting off of the drill pipe ?

MR PAXTON : Dealing first with the question concerning salt water; if you are drilling a salt-bearing formation and the drilling fluid is already saturated, it does not absorb more salt, therefore enlargement of hole does not occur. Salt water is not satisfactory for all types of conditions, however, and its successful use is dependent on suitable sub-surface conditions.

MR MASTERSON : You mean that the whole formation must be saturated ?

MR PAXTON : No; it should not be used in unstable shales, for instance, or unconsolidated formation. There is no hard and fast rule for its use; in some circumstances you can use it, in others you cannot. Salt water may be satisfactory for the conditions existing in Kuwait, but might not be so satisfactory elsewhere. As to twisting off of the drill pipe this is liable to occur, but recovery is usually not difficult.

It is part of my job to be cost-conscious. In relation to loss of circulatiin I would recall the remarks of an earlier speaker who referred to oil-base muds; their use as general purpose muds would prove terribly costly if any question of loss of circulation were involved.

THE PRESIDENT : We have had presented to us a most interesting paper, and I am sure you will all wish to join with me in thanking Mr Paxton very much for it and for having provoked a very useful discussion.

(The thanks of the meeting to Mr Paxton were expressed with acclamation, and the proceedings terminated.)

THE EVALUATION OF ENGINE LUBRICATING OILS

By Norman Kendall * (Associate Fellow)

This paper deals not with the mechanics but with the philosophy of the subject of engine oil evaluation. It is not concerned with the details of the various test methods and test conditions, except incidentally and by way of illustration, but rather with the fundamental concepts underlying the development and application of rational test techniques. The philosophical aspects of this subject are of primary and the utmost practical importance not only to those concerned with the development, operation, or specification of test procedures, but also to engine operators and to those wishing correctly to appraise an oil on the basis of test results obtained in the laboratory. It has become increasingly obvious that confusion of thought exists on the methods and aims of the evaluation of engine lubricating oils, and as a result much time and money has been wasted on meaningless tests. Quite arbitrary test procedures have found their way into specifications; errors in judgment have occurred through a failure to appreciate the significance or limitations of certain test methods and specifications, and by the application of test methods which were not really pertinent.

The purposes of the present paper are to review what should be the aims in evaluating an engine lubricating oil, to discuss how these aims can be achieved, to consider the significance of evaluation tests, and to show how they should be applied in appraising an oil. By way of example references are made to some typical standard test procedures which have been in use for several years at the Thornton Research Centre of The Shell Petroleum Co. Ltd. and on which a large background of experience and confidence has been built up.

General Performance Level

The only ultimate criterion of the quality of an engine lubricating oil is its performance in the field. This basic principle is apt to be lost sight of in laboratory evaluation; the operator, in particular, soon comes to appreciate that as far as he is concerned some oils are better than others, some are quite satisfactory, while others may be outstandingly good or outstandingly bad. He thus develops the idea that oils may be graded, or put on a scale of quality, according to the general level of performance which they give in his engine. He then goes on to demand simple and rapid methods of evaluating lubricating oils in terms of the performance he may ultimately expect of them in the field and to incorporate such methods in the specification against which he will buy his oils.

* The Shell Petroleum Co. Ltd., Product Development & Research Dept. (formerly of Thornton Research Centre).

This concept of a general performance level (GPL) is now well established, and although it is doubtful whether anyone would attempt to give a definition in generally valid, rigid, and comprehensive terms, the existence of the concept and the desire to put it on a quantitative basis is manifest in many ways. For instance, many engine tests have been devised which attempt to express the GPL of the test oils in terms of some rating system. Again, for some purposes it is often convenient to arrange lubricating oils meeting certain typical and familiar specifications according to the scale shown in Fig 1. (It should be noted that supplemental List 1 Classification referred to therein has no official designation since the abolition of the 2–104B specification.) Still further, the concept of a GPL is implicit in

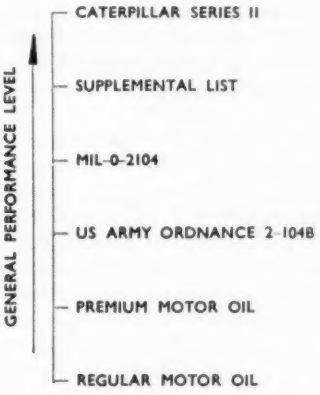

FIG 1

ARRANGEMENT OF SOME TYPICAL ENGINE LUBRICATING OIL SPECIFICATIONS AND DEFINITIONS ON A SCALE TO ILLUSTRATE THE CONCEPT OF GENERAL PERFORMANCE LEVEL

the many lubricating oil specifications which have included a single engine test intended to provide a guide to the quality or all-round performance of an oil in the field. From many such indications it is clear that too often and too widely the GPL of an oil (or its rating, or grade, or its ability to meet certain specifications, or whatever other terms may be used to express quality) has come to be thought of as a single immutable characteristic inherent in the oil, which is an index to the performance which may be expected of it in service. It thus becomes a property as peculiar to the oil as its viscosity or any other physical characteristic, and should therefore be amenable to elucidation and quantitative expression if only the appropriate test method and test conditions could be devised.

Such a simplified concept of GPL is quite wrong, however, as is obvious when it is considered that the performance of an oil depends ultimately on three primary factors :—

(i) the properties of the oil itself;
(ii) engine design;
(iii) engine operating conditions.

Each of these factors is itself comprised of a large number of independent factors, so that their combined effect on the GPL of the oil is very complex indeed.

A particular combination of engine design and operating factors will often make a particularly heavy call on certain of the properties of the oil, and if these exist to an adequate extent the GPL of the oil will be regarded as relatively high. In another combination of engine design and operating factors, other properties are likely to be required which the same hypothetical oil may be lacking, and its GPL in this case will be regarded as poor.

The performance of any oil, relative to some reference point in any one engine, will therefore not necessarily be the same in any other engine or indeed even in the same engine under other operating conditions.

It follows that although a laboratory engine test which agrees in its discrimination between oils in a particular application in the field may be developed, this test cannot be expected to be in similar agreement with other engines and other applications.

However attractive, then, might be the laboratory evaluation of GPL—and undoubtedly it *is* attractive—the conclusion can only be that in the very nature of the problem it is impossible to attempt evaluation of the GPL directly in the laboratory. In fact, such a property does not exist, and strictly speaking GPL should not be referred to except in connexion with the performance of an oil when subjected to particular operating conditions in one particular engine. Nevertheless, it remains vitally necessary to evaluate engine oils in the laboratory, and as it is impossible to do so in terms of a single assessment of GPL, then some other basis of evaluation must be sought. Such a basis, the principles of which form the thesis of the present paper, may be referred to as the specific evaluation of lubricating oils.

Specific Evaluation of Lubricating Oils

First, the role of the lubricating oil in the operation of an engine must be considered. Too often the engine is regarded as being the concern primarily of the drawing office, the metallurgist, and the production shop, and it is not until the prototype is on the test bench for the first time that much consideration is given to the oil to be put in the crankcase; the oil is thus a minor, though essential, afterthought, almost like remembering to fill the radiator. Now it would be of considerable benefit if this outlook were changed and the oil thought of rather as an integral and major material of construction of the engine, of a status equal to that of the bearing materials, the crankshaft, liners, pistons, and rings, or any other critical component. The oil is admittedly a consumable material, but so also are the spark-plugs and any other critical parts.

This conception of the role of the lubricating oil is by no means original, but it has never really been seriously adopted. If the oil be considered in this way several implications ensue. The oil must be taken into account much earlier in the design and development stages; the engine may even to a considerable extent be designed around the oil, particularly if development has reached the stage where the oil performance is the limiting factor

to engine overhaul life. But of greater interest to us in the present connexion, is the inference that if the oil be considered simply as one of the many different materials of construction, then there is no reason why its performance, or its quality, should not be determined on precisely the same basis as the other materials.

Consider, for example, the evaluation of some other critical material of construction, say the steel for some highly stressed component. On the basis of experience or experiment the nature and level of the specific properties required in such a component are decided upon. These may in a particular case be tensile, impact, and fatigue strengths, elastic properties, and surface hardness. A sample of the steel proposed for use is then subjected to tests in respect of each of these properties in turn, and acceptance of the material, so far as performance is concerned, will depend on its meeting the level required separately for each property. No one, so far as is known, has yet attempted to assess the suitability of such a steel specimen in terms of an overall assessment, corresponding to a GPL, by submitting it to a single comprehensive test consisting of the simultaneous application of a push-pull-twist-and-a-swipe. Yet many have had the temerity to attempt exactly this in evaluating a lubricating oil.

A comparison of the fundamentals underlying the evaluation of lubricating oils with those underlying the evaluation of other engine construction materials is a very valid and close one. It is more than an analogy; the cases are identical, and their comparison can be pressed to the fullest extent to emphasize the essential principles of the evaluation of lubricating oils, to indicate the nature of the tests required, and to guide the interpretation, application, and limitations of the test results.

In the evaluation of a lubricating oil then, three steps may be distinguished :—

(i) the individual and specific properties and characteristics pertinent to the intended application must be identified, and the degree to which each is required must be determined or decided upon in some manner;

(ii) methods of evaluating each of these specific properties must be developed if not already existing;

(iii) an oil is then considered satisfactory if for any particular application it meets the requirements in respect of each of the pertinent specific properties.

This, then, is the basic philosophy on which engine lubricating oils should be evaluated for purposes of development, sale, or purchase and on which specifications intended for ensuring quality and performance should be founded. For ease of reference this principle may be termed the " specific evaluation " of engine lubricating oils, in contrast to the outlook which attempts to assess an overall GPL.

From what has been said it follows that engine lubricating oils cannot in general be assessed or rated in single or absolute terms, but must always be evaluated with reference to the particular application for which they are intended. Thus, without qualification, an oil should not be referred to simply as being " better " or " worse " than another, any more than one piece of steel can be said generally to be " better " or " worse " than another. For a certain type, or types, of operation it might be permissible

to make a comparison of oils in such terms; frequently in practice the actual concern is with somewhat restricted types of application (for example, four-stroke automotive diesel engines in some particular type of service, or normal passenger car gasoline engines), when it may become possible to consider lubricating oils on a common scale of assessment, but in all such cases the restriction must be implicit if not declared.

Reference was made earlier to disappointments in the development of superior motor oils. The only official guidance given on the subject of standards is in terms of nomenclature. This is presently under review by the API, but the current definition, given in the SAE Handbook (1951) for the term " Premium Type " is a " Motor oil having oxidation stability and bearing corrosion-preventive properties necessary to make it generally suitable for use in internal combustion engines where operating conditions are more severe than regular duty." By some rather obscure process of

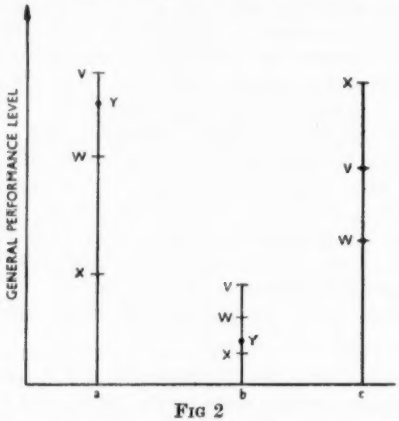

FIG 2

RELATIVE GENERAL PERFORMANCE LEVELS IN DIFFERENT ENGINES

reasoning this has come to be interpreted as implying the maximum permissible CRC L-4 bearing weight loss, the level of which varies according to the authority recognized, but is normally in the order of 400 mg or less per whole bearing and seems to have been decided upon quite arbitrarily. It has been found in practice, however, that in normal automotive gasoline engines outstanding oxidation stability and L-4 performance are not the most important requirements, but that factors such as sludging, wear, ring plugging, rusting, and low temperature performance generally are of far more importance. Thus, in many field tests it has been found that certain " Regular " grade straight oils having a good accommodation for fuel and combustion products have given performances in automotive service superior to the purely highly anti-oxidant additive type of " Premium " oils. In such cases the regular grade oils have sometimes had L-4 bearing weight losses in excess of 1000 mg, but have given no trouble in service. This experience contains several useful lessons. First, it emphasizes that stage (i), the determination of field requirements, must be accurately determined. In this case it was simply assumed that an oil with greater

oxidation stability must be a " superior " oil. Secondly, it illustrates that without reference to the application it is not possible to evaluate an oil. Thirdly, the case illustrates the mischief which can be caused by losing sight of the original purpose of a specification and by working to what becomes virtually an arbitrary specification. The work of those concerned with the development of lubricating oils is made disproportionately more difficult by the fact that they have frequently a two-fold aim ; the oil must first pass an arbitrary specification, laid down by the consumer, and it must additionally and quite independently, ultimately prove in service to be technically satisfactory. The consumer is unfortunately so often his own executioner in that he is apt to lay down his arbitrary specifications, either in complete ignorance, or because, quite understandably, he does not know how to safeguard his interests properly so far as the more important aspects of lubricating oil performance are concerned.

Aims of Testing

So far consideration has been given to the testing of an engine lubricating oil only as the evaluation of its performance level in general service in the

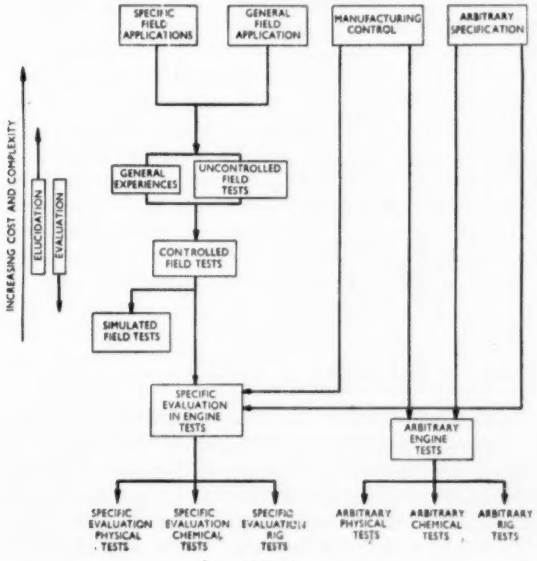

FIG 3

RELATIONSHIPS BETWEEN VARIOUS TYPES OF TEST

field. In carrying out tests to assess an oil, however, four separate and ultimate, or primary, possible aims may be distinguished :—

(i) to predict general field performance;
(ii) to predict performance in specific application in the field;
(iii) to afford manufacturing control;
(iv) to fix arbitrary specifications.

The types of tests which can be used for each of these purposes, and the inter-relationships of the tests, are shown diagrammatically in Fig 3, in which descending order represents decreasing complexity and cost. The various aspects of each of these types of test and the aims which they are intended to meet may usefully be considered in brief.

General Field Performance

The determination of field performance may be considered to fulfil two separate functions, elucidation and evaluation.

The first of these, elucidation, is the means by which may be determined both the nature and extent of the field requirements in terms of specific

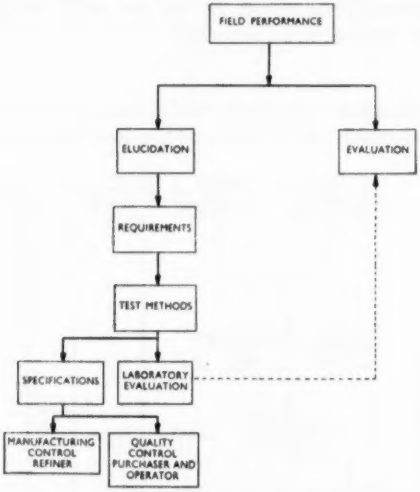

FIG 4

FUNCTIONAL RELATIONSHIP OF VARIOUS TYPES OF TEST

properties. On the basis of this knowledge suitable test methods may be established to provide tools for the laboratory evaluation of lubricating oils. At the same time these test methods enable sound specifications to be framed for the benefit of the manufacturer and the operator (Fig 4).

The ultimate criterion of the overall quality of a lubricating oil, and the only thing that really matters technically, is its performance in the field. Assessment according to field performance is, then, the only primary means of overall evaluation available and the only evaluation from the results of which there is no appeal; all other methods can at best be considered only of secondary status. On the other hand, from the point of view of simplicity and economy it is always desirable to make use of laboratory evaluation and to make such evaluation identical with that derived direct from the field. There are, however, several weaknesses in the chain of processes between field performance and laboratory evaluation (Fig 4) which inevitably result in errors and inaccuracies. In the first place the

process of elucidation is an extremely difficult and complex one to resolve in specific terms, and very frequently factors which are most pertinent in field performance remain unrevealed or imperfectly understood. Furthermore, it is extremely difficult to devise valid test methods, especially engine tests, to measure only the property concerned, since such methods are liable themselves to introduce almost as many complex and confusing factors as the original field conditions.

Sometimes the logical evolutionary line of development of test methods via the process of elucidation (Fig 4) is found too tedious, and an attempt to short circuit it is made by proceeding straight from evaluation in the field to the development of methods of evaluation in the laboratory based purely on empirical correlation. This is a rather hazardous procedure, however, as ignorance remains of all the factors involved. The measure of correlation achieved is likely to be very restricted while the limitations of the test are unknown.

Specific Field Applications

The consideration of general field performance, which involves the evaluation of the performance of the lubricating oil under all conditions of engine design and operating conditions, is a formidable task, especially since the requirements in different types of operation are frequently mutually exclusive, and therefore impossible to satisfy in a single oil. In fact, the task is virtually impossible, to the regret particularly of the oil producer, who naturally wishes to satisfy the greatest number of applications with the smallest number of oils. In practice, then, the complexity of the subject is reduced by narrowing the interest at any one time to more specific applications. This can be done by considering aviation, automobile (gasoline), and diesel lubricants separately. Each of these can then further be broken down into still more restricted fields, such as normal automobile service, light-duty low-temperature delivery type service, heavy-duty long-haul truck service, and so on. Such classifications will still involve an appreciable range of operating conditions, but must be regarded as about the optimum from the point of view of the oil producer. From the operator's point of view, however, it is frequently desirable and possible to narrow the field of interest still further and even ultimately to consider perhaps one engine running under closely definable operating conditions. The distinction between specific and general field application is thus really only one of degree, but recognition of the distinction is nevertheless important, as so much depends on the extent to which the interest can be restricted. The more specific the interest can be made, the easier is the job of elucidation and evaluation, the greater the accuracy of the laboratory evaluation, and the easier is the work of framing specifications; on the other hand, all results are of correspondingly restricted application, and extrapolation to other conditions becomes increasingly more difficult.

Field Tests

Whatever the degree to which conditions can be simplified by restricting attention to more specific applications, the first stage in the elucidation and evaluation of lubricating oil performance is to acquire the relevant back-

ground data, which may be obtained from both planned field tests and from general field operating experience. Field tests may be either "uncontrolled" or "controlled."

Uncontrolled field tests consist in taking the necessary observations from a relatively large number of engines operating normally but within the restricted conditions in which there is a particular interest. This is in effect a Gallup poll carried out on a random sample of such engines of a size sufficient to allow handling of the data on the basis of statistical analysis.

Controlled field tests consist in operating a number of engines under controlled conditions representative of those to which interest is restricted.

Both types of field test have their attractions and limitations. Uncontrolled tests can be lengthy, and often the data are unwieldy. Controlled field tests may be less time-consuming, but the valid range of applicability of the results may be either more restricted or less certain. Both controlled and uncontrolled tests must be backed by adequate general field experience, and this is of such importance from many points of view that it is included as a separate factor in Fig 3. Experience will itself provide a solution to many problems associated with the evaluation of lubricating oils, and it must be available in generous proportions to supplement field test data in the development of laboratory tests. Without adequately wide experience many pitfalls await anyone attempting to set up laboratory tests or to interpret the data from such tests. Controlled field tests must be planned on a fairly precise knowledge of the nature of the problem concerned and with the ability to recognize pertinent factors; without sufficient experience it is not possible even to select a proper field sample, much less to define valid operating conditions under which the tests are to be run.

Controlled field tests, being thus so dependent on previous experience and/or on the results of previous uncontrolled field tests, are in a sense later in the evolutionary scale shown in Fig 3. The purposes of uncontrolled field tests therefore are much more nearly concerned with the function of elucidation, whilst those of controlled field tests are much more nearly concerned with evaluation. An error which is sometimes made is to use controlled tests for the purpose of elucidation when uncontrolled tests would have been the more legitimate medium.

In translating back to the field the results of laboratory evaluation, controlled field testing is frequently resorted to. The success of such tests depends very largely, first, on the accuracy with which the analysis of the problem has been made, since this affects the validity of the operating conditions chosen, and second, on how specific the application is, since this restricts the complexity of the problem.

Simulated Full-scale Tests

With full-scale tests intended to simulate conditions obtaining in a particular engine operating to a clearly definable schedule, an attempt was made to bring the problem of evaluation into the laboratory for the first time. Such tests are carried out with the engine mounted on a test bench, operating conditions being designed to simulate some particular type of operation in service, such as, for instance, city bus service, heavy-duty

long-haul truck service, or constant load generating and pumping set conditions.

This type of test apparently is very simple, and has the merit that results are obtained in a full-scale engine operating under conditions which may bear close relation to practice. It may be attractive, especially where the interests of a particular manufacturer or operator are concerned. For more general application there are several disadvantages and weaknesses to consider, however. The results are, of necessity, of very restricted applicability; they concern only one particular type of engine (perhaps even only one engine) operating under somewhat arbitrary conditions, for it is seldom, if ever, possible to decide what really are representative operating conditions in the field; these vary so widely from one engine to another, from one operator to another. Frequently, too, it is impracticable to simulate too closely the field conditions, where operating conditions may involve a test length corresponding to 50,000 miles or more and a total elapsed time of a year or so. It is then necessary to adopt some means of accelerating the test, so that instead of running a test simulating field conditions the result is a test simulating field end results, with all its concomitant weaknesses.

The attempt to set up a simulated full-scale test is an acknowledgment that the number of complex factors is too great for them to be identified, or even for their relative importance to be assessed. In order to circumvent this ignorance the laboratory attempts to reproduce conditions identical with those presumed to obtain in the field with the idea that the factors involved, whatever they be, will also prevail with unchanged interrelationships.

Simulated full-scale tests have a very useful place both for the operator or the manufacturer and for the oil producer, particularly before taking a new oil out of the laboratory for the first time. They may be regarded as the final laboratory evaluation of an oil intended for some specific application, to be carried out after all the more usual types of laboratory evaluation have been completed, or they may be regarded as screening tests to the field, just as in the laboratory itself relatively rough and simple screening tests are carried out initially before passing the oils to more expensive and more valuable tests. Simulated full-scale tests should not be used for general evaluation purposes; apart from being too expensive their specific significance is insufficiently defined. Nor should such tests be used for general specification purposes, since their applicability is too specific and too restricted. They are most valuable when in the fullness of time the cumulative experience on a wide range of engine types and oil formulations becomes available.

Specific Evaluation : Engine Tests

Specific evaluation of lubricating oils in engine tests involves the evaluation of each pertinent specific property of the oil in some suitable engine and under appropriate test conditions. The test engine is simply a laboratory tool, and the fact that the type of engine or the operating conditions bear little or no similarity to practical conditions is of no importance.

Identification of the pertinent specific properties in any particular case,

or definition of the terms used to signify such properties, can rarely be achieved in fundamental terms or even without reference to conditions in an engine. This admittedly is a disadvantage; however, the terms used usually present little difficulty to one familiar with lubricating oil performance in an engine. The more frequently encountered specific properties may be listed in terms such as the following :—

Bearing corrosion;
Combustion chamber deposits;
Compatibility with other oils;
Cylinder bore lacquering;
Detergency (or antiflocculation);
Filter blocking (various types);
Fuel accommodation;
Lubricating oil consumption;
Octane requirement increase;
Oxidation stability;
Piston oil ring plugging;
Piston ring sticking;
Piston ring groove packing;
Piston undercrown deposits;
Physical properties (cold starting, friction loss, etc.);
Rusting;
Sludging;
Spark plug deposits;
Two-stroke port blocking;
Valve deposition;
Valve burning;
Wear (bore, rings, crankpins).

In addition unusual specific properties demanded for certain cases have to be taken into account, for example, ring scuffing or silver bearing wiping. In such cases these properties must be considered for the formulation of a prescription type oil which may be used temporarily as a palliative until such time as what is really an engine design defect may be remedied.

The above list of the properties is not to be taken as definitive, nor are they by any means all simultaneously applicable in any particular case. Many of them are not independent or absolute in nature; some of them are expressed in terms of the properties of the oil, some in terms of an engine manifestation. Thus, for instance, in any particular case ring-sticking may be dependent on oxidation stability or detergency or fuel accommodation. The terms in which the pertinent properties are expressed in any particular case are immaterial; what matters is that the mechanism and manifestation involved in service are correctly identified and reproduced in the laboratory evaluation. In this connexion the mechanism, incidentally, is of far greater importance than the manifestation. In many cases, some of the properties have to be considered on the basis of several mechanisms independently. Thus, sludging or wear may each be encountered under different types of operating conditions, and must be evaluated accordingly.

The principle of specific evaluation is the most fundamental and logical, and even though it must often be applied through the medium of test engines, it remains the simplest and most generally applicable means of assessing a lubricating oil. Specific evaluation in engine tests is thus by far the most important type of lubricating oil testing and the one mainly concerned here; discussion is deferred until later, when it can be dealt with in greater detail.

Specific Evaluation : Laboratory Tests

The ultimate in simplicity is the " test-tube " type of test carried out in the chemical or physical laboratory. Many attempts have been made at such tests, many claims made for various tests, and many disappointments encountered. Quite frequently such tests have been established without due regard to the requirements or conditions of the field; in other words, the process of elucidation has not been satisfactorily completed or has been completely ignored. Tests have been proposed often with little justification other than simplicity or on the false premise that one or other particular property was the sole criterion of lubricating oil performance. Various types of oxidation test have been particularly favoured.

Owing to the immense complexity of the processes involved in lubricating oil deterioration and performance, the improbability of all the factors concerned ever being elucidated, and in view of the variations and changes in combinations of the factors which occur even in specific applications, there is little prospect of engine tests ever being replaced completely by laboratory tests. Nevertheless, such tests can in many cases be made to fulfil a most useful function, particularly as adjuncts to engine tests of all types and in following the course of lubricating oil deterioration rather than in attempting an absolute assessment of oils. In certain applications there is often a possibility of establishing laboratory tests which correlate with engine tests to a degree sufficient to make them useful for screening purposes. Such correlation is always on an empirical basis, however, with no certainty as to the limitations to the validity of the test, or whether some types of oil may not be subsequently encountered which do not conform to the correlation. In any case the specific nature of such tests and the significance of the particular property concerned should never be lost sight of; from this point of view it is desirable to reconsider the importance of many of the tests presently insisted upon in some specifications.

Manufacturing Control

Manufacturing control is not really of concern here, but nevertheless is dependent upon evaluation. Logically, control should be based on specific evaluation, and should be guided by the requirements of any particular application. In practice, however, the more usual concern is maintenance of product uniformity in manufacture, rather than in attaining a given level of performance, and accordingly it is often felt that specifications of physical and chemical properties, such as viscosity, colour, flash point, etc., are adequate for this purpose. This might be quite satisfactory for control purposes, when applied to manufacture from one crude source and one refinery process and where the performance of the oil in the first instance was satisfactory, but unfortunately the idea has become rather widespread that such specifications were adequate for the general control of quality irrespective of these considerations. Thus, arbitrary engine tests, and even more so, arbitrary physical and chemical tests, from serving a more or less legitimate purpose of refinery plant control have frequently come to be misapplied to the general evaluation of lubricating oil performance. This has resulted in unnecessary restriction on the oil producer, and is very frequently against the interests of the operator, both economically and technically.

In place of arbitrary engine tests, legitimate specific evaluation tests have been successfully applied in the course of lubricating oil manufacture, particularly where improvement of base stocks, refining conditions, additive susceptibility, or the development of additives has been the aim. In the application of specific evaluation engine tests to such work it is of interest to observe that real and practical differences, confirmed later by more elaborate analytical chemical work, have often been revealed which were not shown up by differences in the conventional tests for physical and chemical properties.

Arbitrary Specifications

Arbitrary specifications arise from many sources. Often they are merely carried over from manufacturing control specifications in the belief that they provide an adequate and absolute safeguard of quality. Sometimes they are derived from empirical sources or because an oil which has performed satisfactorily was found to have certain properties which had been subsequently incorporated in a specification. Frequently specifications have been handed down like heirlooms and adopted, not because there is any sound basis for believing that they have any significance, but because they have been used by other authorities—probably by several in succession. Such specifications are most pernicious, because so much respect becomes attached to them, and in the course of time a tremendous background of data is accumulated which people are loth to throw away.

Sometimes in framing a lubricating oil specification the body concerned will simply incorporate an existing engine test from some other specification. This may be done because it is desired to fall in line to some extent with the standards of the original specification, but very frequently it is done in ignorance or laziness, and in disregard of the fact that the requirements of the original specification which the engine tests in question might have covered quite satisfactorily, might be quite different from those for which the new specification is being set up. This plagiarism, instead of serving any useful purpose, simply results in a pitifully pale shadow of the original specification and adds one more restrictive demand in the path of oil development which is particularly of detriment to the user.

Another type of arbitrary specification engine test sometimes crops up which is of even more doubtful legitimacy. Perhaps the authors of the specification wish, as above, to follow the standards set by an existing test, but for reasons of economy or expediency decide to adopt an engine test which is supposed to give results in agreement with the original test. This procedure could, of course, be used quite satisfactorily, although experience shows that evidence of correlation is usually very inadequate; and one views with considerable suspicion the type of test in which correlation with a primary standard is claimed on the basis of unrelated performance criteria.

It is sometimes impossible to market a good oil which does not meet arbitrary specifications; on the other hand, it is possible to market a poor oil which does meet such specifications. Moreover, as a rule it is easier to meet such specifications than to produce a good oil. The established oil producers who cannot afford to risk their reputation have therefore the difficult two-fold job of producing oils which, in addition to being technically good, have also to meet the arbitrary specifications.

Specific evaluation engine tests can be used to evaluate oils with respect to their meeting the requirements of arbitrary specifications (see Fig 3). This is simply because the arbitrary specification frequently implies, possibly without its author being aware of the fact, the imposition of requirements in respect of some particular property. In such a case there is no reason why appropriate specific evaluation tests should not be used, particularly for screening purposes, if they be more convenient. This will not improve the legitimacy of the arbitrary specification, however, if the properties evaluated do not correspond with those of the field.

As knowledge on the significance and principles of lubricating oil evaluation tests increases, the use of arbitrary tests will tend to diminish and eventually disappear.

Further Discussion of Specific Evaluation in Engine Tests

The relationship between the various types of test, indicated in Fig 3, have been considered broadly and brief reference made to the outstanding importance of the specific evaluation of lubricating oil engine tests. This latter aspect will now be discussed in greater detail.

In attempting evaluation of an oil, all the pertinent specific properties must first be identified on the basis of either general experience or systematic observations in the field and the extent to which each property is demanded in the particular application in mind decided. Then any oil proposed for this application must be evaluated with respect to each of these specific properties. Thus, it may be decided that specific properties, A, B, C, D, E, F, . . . X, are pertinent and that the required level in respect of each of these is a_r, b_r, c_r, d_r, e_r, . . . x_r respectively. On evaluation, the test oil is found to possess the pertinent specific properties to an extent a_t, b_t, c_t, d_t, e_t . . . x_t respectively. This may be set out as in Table I.

TABLE I

Specific property . . .	A	B	C	D	E	F	. . . .	X
Requirement . . .	a_r	b_r	c_r	d_r	e_r	f_r	. . . .	x_r
Test oil evaluation . . .	a_t	b_t	c_t	d_t	e_t	f_t	. . . .	x_t

Thus, to be *just* satisfactory it is required that $a_t = a_r$, $b_t = b_r$, $c_t = c_r$ . . . $x_t = x_r$. The deficiency or the margin in hand of the test oils in respect of all these properties represents the degree to which the oil is deficient or more than sufficient, respectively, for the purpose in mind. If it is deficient in one property only then the oil must be further developed with respect to this property or else considered as unsatisfactory.

The primary interest here, then, is in devising the means of evaluating the specific properties, A, B, C, D, E, F, . . . X. With only the slightest knowledge of the subject it is obvious from the outset that a single comprehensive test of any sort is likely to be quite inadequate. No single property can be allowed to be submerged in a general " blanket " type of evaluation; an outstanding superiority in property A, which may result in a superior overall assessment in a comprehensive type of test, cannot compensate for the fact that the oil may be deficient in property B, and will therefore prove

unsatisfactory in the field in this respect. The strength of the chain is the strength of its weakest link.

Reverting for the moment to the concept of a general performance level, it can be seen that in any case this would be represented, not by a single all-embracing cipher, but by a complex pattern of performance, represented by a_t, b_t, c_t, d_t, e_t, f_t . . . x_t, very intimately associated with the particular conditions of engine design and operation. In another case, where the requirements may be met by an oil having properties a_w, b_w, c_w, d_w, e_w, f_w . . . x_w, the GPL will be represented by a quite different pattern of performance. In general, it cannot necessarily be said that oil w is superior or inferior to oil t; the two oils are in fact equal in the sense that each exactly meets the requirements of the particular application for which it is intended.

The oil must, then, be evaluated in respect of each and every specific property. If there are n properties concerned, means must be available for evaluating each one. This does not necessarily mean that n test procedures are needed, however, since it may be possible to evaluate two or more properties in one test, if they are of a nature such that they are exhibited under similar types of operating conditions.

Reference was made earlier to the impossibility of developing a single engine test which will evaluate engine lubricating oils in terms of a generally valid GPL and to the reversal in relative ratings which is frequently encountered when submitting oils to different engines or to different operating conditions (Fig 2). Some of the reasons for this can now be readily appreciated when the evaluation of an oil is conceived as a complex pattern of performance rather than as a single overall assessment.

In any one engine, and under one particular set of operating conditions, the performances of a series of oils could be evaluated. As already observed, such evaluations would have no meaning if not referred to the particular engine and operating conditions, but would exist in virtue of the pattern of performance of each oil and only under very specific conditions. In these circumstances it can be argued that the same order of evaluations can be produced in a second or test engine only if conditions in that engine can be arranged so that the performance pattern of each oil in the prototype engine is reproduced with geometric similarity in the test engine.

Since this reference to the geometry of the performance pattern is rather metaphorical, it may help to clarify this argument by referring to Fig 5. Consider two oils V and W, run in a prototype engine P and in the test engine T and rated relatively in each engine as indicated by the positions of V_p, W_p and V_t, W_t respectively on the vertical scales. In the prototype engine the relative rating V_p is attained in virtue of the general pattern of performance a_{vp}, b_{vp}, c_{vp}, . . . etc; that of W_p is attained in virtue of the general pattern of performance a_{wp}, b_{wp}, c_{wp}, . . . etc.

In the test engine the positions of $V_T W_T$ are similarly consequent on the patterns of performance a_{vt}, b_{vt}, c_{vt}, . . . etc., and a_{wt}, b_{wt}, c_{wt}, . . . etc., respectively. Now the patterns of performance a_{vp}, b_{vp}, c_{vp}, . . . and a_{wp}, b_{wp}, c_{wp} are in general unlike; in other words, although a_{vp} may be greater than a_{wp}, it may be that b_{vp} is less than b_{wp}, etc. Similarly, in the other engine the patterns a_{vt}, b_{vt}, c_{vt}, . . . etc., and a_{wt}, b_{wt}, c_{wt}, . . . etc., are unlike. Now if the patterns a_{vp}, b_{vp}, c_{vp}, etc., and a_{vt}, b_{vt}, c_{vt} (that is,

the patterns for any one oil in the two engines) are also unlike geometrically (it does not matter that they may differ in magnitude), it is inconceivable, when a large number of oils is concerned, that the relative positions of V_p, W_p, etc., in the prototype engine can be reproduced in the test engine. From experience it is known that unfortunately it is virtually impossible to arrange conditions in a test engine such that this geometric similarity of the performance patterns of a large number of oils in the prototype engine is unchanged; whenever some approach is made to realizing similarity on the basis of a limited number of oils there is always

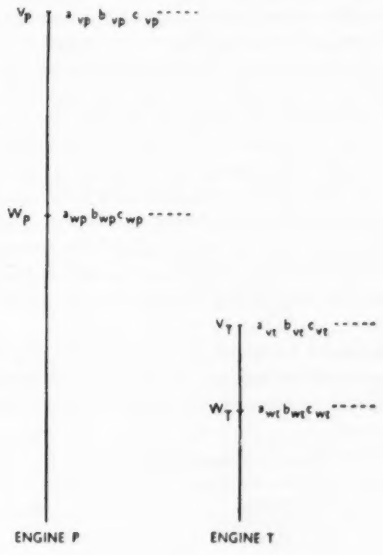

FIG 5

GENERAL PERFORMANCE OF OILS *V* AND *W* IN ENGINES *P* AND *T*

apprehension that some test oil, owing to some peculiarity in its performance pattern, may completely upset the correlation.

On this same argument it is obvious that, in any test correlation work, care should be taken that the oils used as a basis of correlation should not be homologous but should be as mixed as possible as regards type. For instance, to take an extreme case, an homologous series of oils might be taken consisting of a common base oil with various concentrations of a particular type of additive. In such a case it is quite likely that the performance pattern of any one of the series in the prototype engine might be reproduced quite readily in the test engine and correlation thereby claimed. The first test oil to appear with a different performance pattern, however, might completely upset this correlation.

If, then, the test engine cannot reproduce unchanged the performance pattern of each oil in the prototype engine, it must be concluded that it is not possible to develop a test method to evaluate the GPL of oils so as to

predict their performance in general service. The argument now used is only a more pedantic way of expressing what has previously been said : that the performance of an oil cannot be dissociated from the specific engine and operating conditions concerned and that differences in engine or operating conditions affect the performance of oils differently.

Reverting to the development of appropriate tests for the specific evaluation of lubricating oils, one of the fundamental difficulties is that the " properties " concerned can rarely be identified or defined in terms of absolute or normally recognized physical and chemical terms. If this could be done, the task of evaluation would be simple. Unfortunately the processes involved in the deterioration of the oil in an engine cannot be fully elucidated. " Oxidation stability " is frequently identified as an important property, for instance, but the effects of the combinations of temperatures, pressures, catalysis, contamination, and other factors are so complex that it is useless to hope that they can ever be elucidated sufficiently to enable us to proceed straight to evaluation in conventional chemical laboratory tests. In this relative ignorance the best course, then, is to use an engine so that all the factors involved, such as temperature gradients, fuel and combustion products, catalytic materials, and many whose existence is not suspected, or which could not be confidently specified, will be present to an extent which might be more closely representative of field conditions than it could be hoped to simulate in the chemical laboratory.

Having decided the need to develop engine tests, the next problem is to decide on the engines most suitable. The principal requirements of a test engine may be listed, not necessarily in order of importance, as :—

Simplicity;
Mechanical reliability;
Repeatability;
Cheapness;
Availability;
Aptitude.

The utmost in simplicity is very desirable in any test engine. It should be regarded simply as a laboratory tool, as a means of introducing fundamental factors such as combustion, blow-by, temperature, oil contamination, and catalysts to the necessary relative degree. In developing an oxidation test, for instance, all that is wanted is an engine in which oxidation of the oil can be achieved under conditions, and to a relative degree, similar to those encountered in service. If the oil is intended for service in a diesel engine it does not even necessarily follow that it must be subjected to a test in a diesel engine, except when the fuel or any other factor is pertinent to the performance of the oil with respect to the particular specific property under consideration.

Apart from economy (first cost, maintenance, reduction in down-time), simplicity also has the important technical advantages of enabling closer control of fitting and operating conditions and easier evaluation of results.

Mechanical reliability is important not only for getting long life from the engine, but also in ensuring constant operating conditions from test to test, and even during test. It is useless to run oil tests in an engine which cannot complete the test without mechanical failure.

Repeatability, and reproducibility, of test results is essential, and in this respect preparation of the engine is most important. It is here that the art of the test engineer, which demands detailed knowledge and the ability to control pertinent mechanical factors, manifests itself. Cheapness of a test engine and replacement of parts is important, since to ensure test repeatability it is necessary to be generous in order to maintain critical parts with close tolerances (pistons, rings, cylinder bores, valves, valve guides, etc.). In considering the adoption of any test method the repeatability and reproducibility in the hands of a number of different operators should be fully investigated on the basis of statistical planning and analysis. The sensitivity of the test to operating conditions should not be such that results cannot be reproduced by different test operators.

Availability of an engine and its spares over an adequate period is highly desirable, and several lubricating oil tests have gained a measure of general acceptance until the manufacturers could no longer supply either the engine or the necessary spares.

Perhaps the most important technical requirement of a prospective test engine is its aptitude for the evaluation of the specific property in mind. To take a simple case by way of illustration, it is no use trying to develop a ring-sticking test on an engine which cannot reasonably be induced to stick its rings; or again, it is no use trying to develop a test for detergency on an engine which does not appreciate detergency and cannot be rendered particularly sensitive to it by any reasonable manipulation of operating conditions. In other words, a test engine must be sensitive, or it must be possible to make it sensitive, to the particular property under consideration. It is in this respect that the idea of using a single engine for evaluating all properties of lubricating oils has its greatest single weakness. It is inconceivable that the design of any such engine could be made so bad that it suffered from all the lubricating oil maladies of interest. In fact, if this were possible the engine would be unsuitable, since when using it to evaluate property A the test might be prematurely upset by the intrusion of property B or C. In designing these " all purpose " test engines it is never known to which properties the engine is going to be sensitive, and this can be illustrated by citing the particular case of a co-operative project (not in the U.K.) for developing a lubricating oil test in a specially designed test engine. The engine was duly designed by a panel and was manufactured; but only at this stage apparently did anyone consider the type of test which was to be developed on the engine. After running it, and smoothing out some initial mechanical troubles, it was found that it had a pronounced weakness in respect of, for example, oil property D. Accordingly, a test procedure was worked out co-operatively to evaluate oils with respect to property D, but no one was particularly interested in property D in the particular type of oils with which the co-operating parties were concerned. So the project has dragged along for several years with insufficient interest even to publish a finally approved specification. A possible answer to the all purpose test engine is the " universal " test engine, which generally consists of a very robust crankcase on which can supposedly be mounted a variety of top assemblies if not all within a certain range of sizes.

Unfortunately in practice such engines prove to be far from universal,

and it is only with the greatest difficulty that two or three different types of top assembly can be fitted. All sorts of difficulties are encountered with stroke dimensions, cylinder bolt hole disposition and type, valve gear, and so on. Apart from expense, universal engines often incorporate all kinds of auxiliary equipment in order to make some approach to universality. In any one test, however, most of this auxiliary equipment is not required. Admittedly, universality and sensitivity to all the specific properties might be attained by the design and construction of special top assemblies and other parts. This immediately becomes complicated and costly and, besides being less flexible, offers no prospect of either economic or technical advantage over a suitable collection of various types of modified industrial engines. The impracticability of these types of engine relates only to their use for general routine evaluations; for fundamental research purposes on oils, fuels, combustion, or engine design they are most useful pieces of equipment.

Without doubt the most useful type of engine for general routine lubricating oil evaluation purposes is the small industrial single-cylinder engine suitably modified where necessary. It is simple, cheap, robust, readily available, and usually one particular design can be selected for its known aptitude. Only in special cases is it necessary to consider more elaborate multi-cylinder engines. With suitable single-cylinder engines generous replacements can be afforded and adequate maintenance ensured, and the engines can be run in batteries for speed of evaluation and for replication of results.

Engine Lubricating Oil Evaluation at Thornton

Thornton is concerned with all the aspects of lubricating oil evaluation, and all test methods are given their due place. Extensive field work is carried out continuously, initially to determine the nature of the problem to be dealt with (elucidation), and ultimately to carry out the final appraisal of newly developed oils (evaluation). The most important laboratory evaluation work is considered to be the specific evaluation in engine tests, according to the philosophy expounded above, and considerable effort is extended in trying to improve such test methods as already exist, as well as to develop new methods where necessary in order to complete the framework of standard test procedures available. Field tests, simulated field tests on the test bench, and general experience in the field all contribute to give a better understanding of the factors involved, and the test methods are improved, as further knowledge is acquired, by a process of successive approximation. At the same time, as quantitative data become available for correlation purposes, every opportunity is taken of improving the physical and chemical laboratory tests which serve for rough screening and control purposes.

The precise way, or order, in which the laboratory engine tests are applied depends in any one instance on the type of oil concerned and on the nature of the requirements, and it would be impracticable to consider here all possible applications. By way of illustration it is proposed to consider the case of evaluating an ordinary HD oil and to give in detail the conditions of some of the tests used.

It will be presumed that a newly developed or newly formulated HD oil

has met the initial requirements in screening tests with respect to physical properties, stability, and so on, and that it has been verified that the oil will meet the conventional arbitrary commercial specification. The oil will then have reached the stage where laboratory engine evaluation is required. Oxidation stability and detergency are regarded as of primary importance, and are evaluated in two separate engine tests carried out in a single-cylinder Petter Series II gasoline engine and a single-cylinder Gardner type L-2 diesel engine respectively. Details of these tests are given in the Appendix. If the oil is deficient in either of these properties to any extent too serious to be dealt with practically, then it may be rejected at this early stage; on the other hand, the deficiency might be remedied by a relatively simple adjustment in formulation, after which it may pass on to the next stage of testing. For many purposes—for screening of HD oils, for control of oils on which background data already exists, for manufacturing control purposes on known additives, and for preliminary evaluation in the course of development of formulations—these two engine tests alone are quite sufficient. But for other purposes, such as the complete evaluation of a new formulation, after the oil has successfully met requirements in the Petter and Gardner engine tests for oxidation stability and detergency it will then be successively submitted to further specific evaluation in engine tests; it would, for instance, pass next to the standard diesel engine ring-sticking procedure, which is carried out in a single-cylinder Fowler engine. After satisfactory performance in this test the oil might then be passed on either to the CRC-L-4 test in the Chevrolet engine or even, particularly if intended for marine application or to meet U.S. Navy requirements, to the seawater test in a single-cylinder National engine. Other engine tests, the order of which would be selected according to the particular circumstances, might include various aspects of filtration, sludging, low-temperature wear, high-temperature wear, general cleanliness and oil ring sludging, the L-1 screening test, and finally the standard CRC-L-1 test itself, or, in the case of Series II oils, the Caterpillar 1-D procedure. If MIL-O-2104 qualification is required, parts from the L-1 and L-4 tests are sent to the U.S. Army Ordnance Review Board for approval, together with all necessary test data and forms. Quite frequently, on completion of all the regular routine test evaluation, the oil may also be put through a simulated full-scale engine test procedure on some particular prototype engine submitted by a manufacturer for examination of its lubricating oil requirements. In any test, failure to meet the level of performance laid down will render the oil liable to rejection or re-formulation, in which latter case it may be considered necessary to put the re-formulated oil again through the earlier tests.

It will be observed that the L-1 test is about the last to be carried out in the laboratory, and, moreover, that a screening test is used to precede it. This is on account of the expense and time incurred in running the standard L-1 test and particularly because the number of engines available for such tests is usually limited. In such circumstances it is always convenient to have a cheap small-scale screening test available. In such screening tests, however as indicated earlier, it is generally preferable to assess performance according to the same criteria as those used in the prototype test.

To give an idea of the nature of the tests involved, brief details and

operating conditions of some of the tests referred to above are given in the Appendix. The code designation given against each procedure is for reference purposes, since on many of the engines a number of different test procedures has been established, sometimes as many as ten or twelve different types of test on one type of engine.

Conclusion

In the course of time a considerable number and variety of engine tests have been put forward very frequently on little or no logical basis and with no ultimate justification other than an accumulated back-log of results. Even in the case of some widely accepted engine tests, established for a number of years, there is very frequently, surprisingly enough, not even any data generally available to show the repeatability and reproducibility of such tests—desirable features of any test method, quite apart from any possible significance of the results.

In recent years, particularly in Europe, there has been an increasing desire on the part of many bodies to draw up more realistic lubricating oil specifications based on actual performance to be expected. This has inevitably led to the desire, quite correctly, to incorporate engine tests in the specifications, but unfortunately there is a real danger that spurious engine test procedures will frequently get into such specifications, thus perpetuating the practice of enforcing quite arbitrary and unnecessarily restrictive specification requirements. It is with this danger in mind that this philosophy of what should be the true principle of lubricating oil evaluation has been put forward; that is, simply the specific evaluation in engine tests of each property of the oil deemed to be significant in the particular field applications in mind. If more than one property is so deemed significant, then evaluation must be in respect of more than one property. In the interests of simplification it may not be necessary to cover all aspects of performance; for instance, it may be decided to cover adequately oxidation stability and detergency, and then, regarding other properties as being only of minor importance, rely for the rest on a general but sufficiently broad clause in the specification restricting the formulation of the oil to the use of approved crudes, refinery treatment, and additives. After all, it is not possible to frame a practical comprehensively water-tight specification; there are tolerances to every engine test, whether recognized or not, and the spirit of the specification is often as important as the letter if these tolerances are not to be exploited. This means, of course, that in running tests to a specification one must :—

(i) have confidence in the integrity of the person running the test, or

(ii) impose a system of inspection, or

(iii) run the test oneself.

It is felt that (iii) is always to be preferred. This is not always practicable, so that (i) may be resorted to, particularly where the test operator is well established and has a long term reputation to safeguard. However, apart from integrity and good intentions, the tester must also be relied upon to have the requisite skill and experience. The system of

inspection is not very satisfactory, since it does not replace the need for integrity on the part of the testers. It must be admitted that this is not an exact science, and not only the engine test, but also the whole process of lubricating oil evaluation depends very much on experience, care, and judgment. There are many weak links between the performance observed in the field and the performance assessed in the engine laboratory; there is first the very difficult task of elucidating the field problem and defining the requirements, there is the difficulty of devising means for legitimately evaluating the various requirements, supposing they can be devised, and there is the difficulty in extrapolating and interpreting the test data accurately when they are obtained. Finally, there is the fact that the engine test is a relatively coarse and temperamental instrument demanding sympathy and more than ordinary manual dexterity if its results are to be significant.

Considerable effort, both in the field and in the laboratory, continue to be devoted at Thornton to improving precision in all aspects of evaluation of engine lubricating oils. Details of some particular engine tests actually in use in the laboratory have been given simply by way of illustration of methods. It is not suggested that these are the only procedures that can be used to evaluate the specific properties in question, or even that they are necessarily the best; all that can be said of them is that they have a logical and practical basis, have been well proven in use, and have been found to serve their purpose well in the evaluation and development of engine lubricating oils. Should there be any further interest in such tests full details, sufficient to enable anyone to operate them, will be made freely available. Should anyone in the future contemplate the thankless task of drawing up a lubricating oil specification, it is hoped that they will avoid the easy acceptance of the most convenient test procedure which may offer itself, but will rather start from fundamentals, first by deciding the requirements which it is required to safeguard in the field, and then by considering and proving the methods by which this may be achieved. With improvements in design and metallurgy many engines are now being developed in which the lubricating oil may well become the limiting factor; in order to ensure continuity of technical advance, it is then all the more important that engine lubricant development is not restricted by ill-considered specifications, but that it should be assisted to the benefit of all involved by being based rather on technically sound and practical specifications.

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APPENDIX

Some Typical Engine Test Procedures Used for the Evaluation of Engine Lubricating Oils

Thornton Test Designation	Engine Used	Purpose	Criterion of performance
PET-LA2 . .	Petter Series II s/c gasoline	Evaluation of straight mineral oils with respect to oxidation stability.	Piston lacquer and condition of undercrown and oil rings.
PET-LA3 . .	Petter Series II s/c gasoline	Evaluation of additive type mineral oils with respect to oxidation stability.	Piston lacquer and condition of undercrown and oil rings.
GAR-PC . .	Gardner L-2 s/c diesel	Evaluation of engine oils with respect to detergency.	Piston lacquer and carbonaceous deposits.
FOW-RS . .	Fowler F.S.8 s/c diesel	Evaluation of engine oils with respect to ring sticking.	Ring sticking.
NAT-SW2 . .	National DAP-1 s/c diesel	Evaluation of engine oils with respect to compatibility with seawater admixture.	Corrosion, sludging, foaming, and separation.

Thornton Designation: PET-LA2

This test is used for the evaluation of straight mineral engine oils with respect to their tendency to form lacquer and carbon deposits on the piston at high operating conditions.

The engine used is a Petter Series II single-cylinder liquid-cooled gasoline type.

The engine is run for a total of 64 hr under conditions of medium speed and load and medium cylinder and high oil temperatures.

The result of the test is expressed in terms of the individual cleanliness merit ratings for piston skirts, undercrown, and oil-control ring deposits. To follow the trend of the deterioration of piston cleanliness these ratings are carried out both at the end of test and after 32 hr.

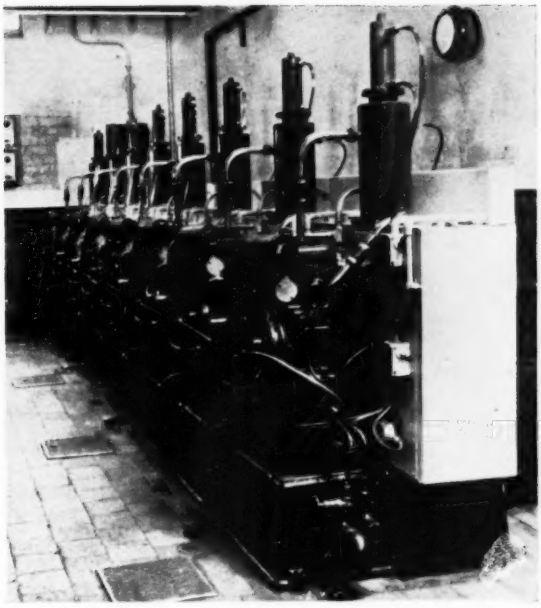
Corrosive tendencies of the oil may be examined by taking oil samples at frequent intervals and submitting them to laboratory corrosion tests. Tendencies to phosphor bronze bearing corrosion are also revealed by the conditions of the small-end after test.

Operating Conditions

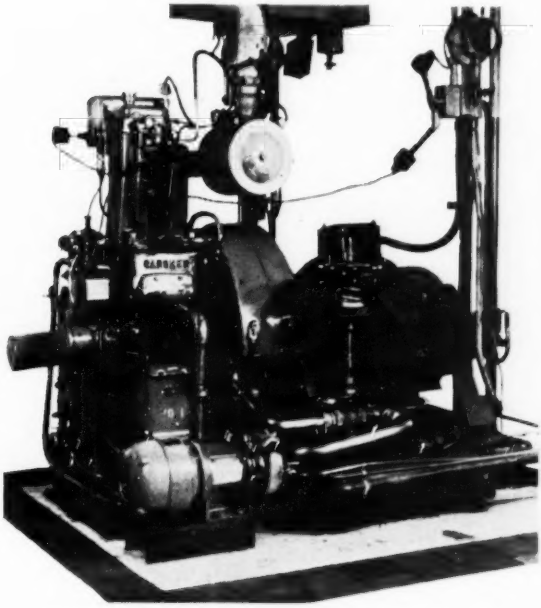
Duration	: 64 hr (in eight periods of 8 hr each)
Speed	: 1540 r.p.m.
B.m.e.p.	: 65 p.s.i. approx
B.h.p.	: 3·6
Induction air temp	: 50° C
Fuel	: Unleaded Billingham hydropetrol
Specific fuel cons	: 0·75 pints/b.h.p. hr
Ignition timing	: 20° b.t.d.c.
Jacket coolant temperature	: 100° C (coolant : water)
Sump-oil temperature	: 130° C
Oil in system	: 3 pints
Oil consumption (uncontrolled)	: 1½ pints per test approx
Make-up oil added	: ½ pint at 32 hr

Thornton Designation: PET-LA3

This test is used for the evaluation of additive-type engine oils with respect to their tendency to form lacquer and carbon deposits on the piston at high operating temperatures. For this test the Petter Series II single-cylinder liquid-cooled gasoline engine is used.

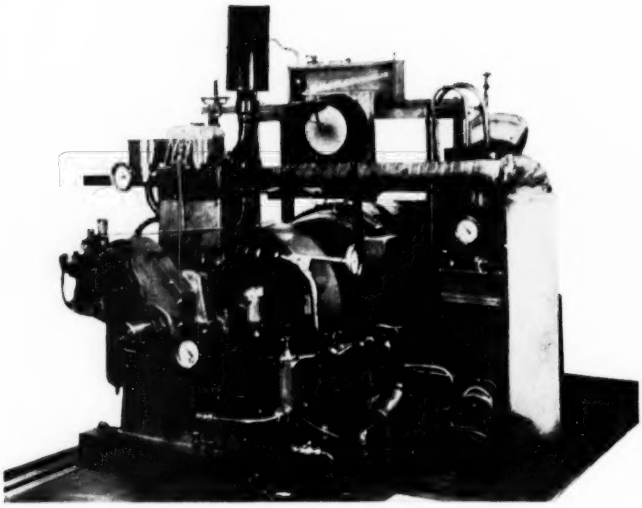


PETTER SERIES II SINGLE-CYLINDER LIQUID-COOLED GASOLINE ENGINES

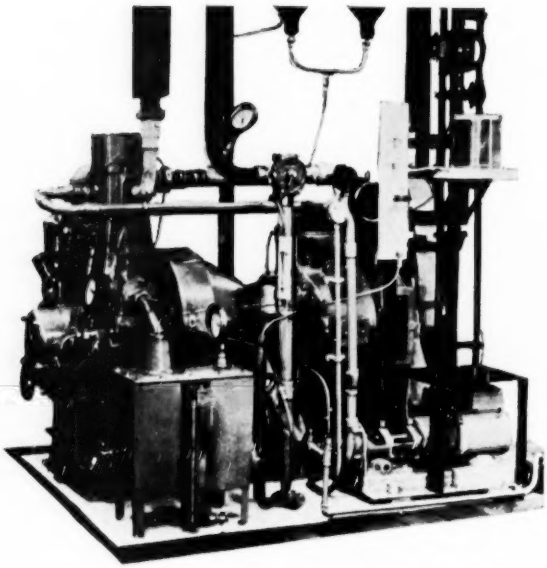


GARDNER L-2 SINGLE-CYLINDER DIESEL ENGINE

[*To face p.* 48.



FOWLER FS. 8 SINGLE-CYLINDER DIESEL ENGINE



NATIONAL DAP-1 SINGLE-CYLINDER DIESEL ENGINE

The engine is run for a total of 48 hr under conditions of medium speed and load and high cylinder and oil temperatures.

The result of the test is expressed in terms of individual cleanliness merit ratings for piston skirt, undercrown, and oil-control ring deposits. To follow the trend of the deterioration of engine cleanliness these ratings are taken at the end of test and after 16 and 32 hr.

Operating Conditions

Duration	: 48 hr (in six periods of 8 hr each)
Speed	: 1540 r.p.m.
B.m.e.p.	: 65 p.s.i. approx
B.h.p.	: 3·6
Induction air temp	: 50° C
Fuel	: Unleaded Billingham hydropetrol
Specific fuel cons	: 0·75 pints/b.h.p. hr
Ignition timing	: 20° b.t.d.c.
Jacket coolant temp	: 160° C (coolant : mixture of 60 parts ethylene glycol to 40 parts water)
Sump-oil temperature	: 130° C
Oil in system	: 3 pints
Oil consumption (uncontrolled)	: 1 pint/test approx
Make-up oil added	: None

Corrosive tendencies of an oil in this test can be assessed in a manner similar to that used in the PET-LA2 test.

Thornton Designation : GAR-PC

This test is used for the evaluation of motor and diesel lubricating oils with respect to their tendency to form lacquer and carbon deposits on the piston under medium-speed, medium-output conditions, and is virtually a measure of the detergent properties of an oil. The engine used is a Gardner single-cylinder, vertical, four-stroke type L-2 diesel engine.

The engine is run continuously for 25 hr under constant medium-speed/full-load conditions. The performance of the lubricating oil is assessed by the quantity of carbon and lacquer deposits on the piston at the end of test; the results are expressed as a visual merit rating.

Test Procedure

Flushing run	: A flushing run of 30 min duration is first carried out followed by oil drain and re-filling.
Duration	: 25 hr continuous running
Speed	: 100 r.p.m.
B.m.e.p.	: 90 p.s.i. approx
B.h.p.	: 10 (approx)
Fuel	: Gas oil containing 1·0%w sulphur
Specific fuel cons	: 3·75 pints/hr
Injection timing	: 19° b.t.d.c.
Jacket coolant temp	
Inlet	: 80° C
Outlet	: 82° C
Exhaust gas temp	: 480° C approx
Sump-oil temperature	: Uncontrolled (65° C approx)
Oil in system	: 6·9 pints
Make-up oil added	: None
Oil pressure	: 20 p.s.i.

Thornton Designation : FOW-RS

This test is used for the evaluations of both additive and non-additive type diesel engine lubricants with respect to ring-sticking properties under conditions of moderately high speed and load.

The engine used is the Fowler R.S.8 single-cylinder, vertical four-stroke compression ignition engine specially designed for bench test work. For the purpose of this test the engine has been suitably modified and test conditions chosen to induce the early onset of any sticking.

The engine is run under constant conditions of moderately high speed and load until ring-sticking occurs. The test is then terminated and the running time taken as the criterion of the performance of the oil with respect to ring-sticking.

The performance of a test oil is assessed by comparison with the performance given by two reference oils which normally give ring-sticking times of 2 and 11 hr respectively. The performances of these reference oils serve not only as a criterion for the ring-sticking times of other oils but also as a check on the repeatability of results.

Operating Conditions

Run up	: The engine is run up to conditions according to a schedule over a period of 35 min; this time is not included in the ring-sticking time.
Duration of test	: Continuous running until ring-sticking is indicated
Speed	: 1500 r.p.m.
B.m.e.p.	: 100 p.s.i. approx
B.h.p.	: 24
Fuel	: Gas oil containing 1·0%w sulphur
Fuel consumption	: 10 lb/hr
Injection timing	: 22° b.t.d.c.
Jacket coolant temp	
Inlet	: 80° C
Outlet	: 85° C
Oil inlet temperature	: 75° C
Oil in system	: 2 Imp. gal.
Oil consumption	: 0·2 pints/hr approx
Make-up oil added	: None
Oil pressure	: 20 p.s.i.

THORNTON DESIGNATION : NAT-SW2

This test is used for the evaluation of diesel engine lubricating oils with respect to corrosion, sludging, and foaming when seawater is added to the oil, and to determine the ability of the oil to separate from the entrained water. The engine used is a National single-cylinder, four-stroke, compression-ignition type DAP-1 engine.

The engine is run continuously for 30 hr at medium speed and load with seawater added to the lubricating oil at a constant rate throughout the test.

The performance of the oil is judged mainly by corrosion of various engine components, sludging, foaming in the oil tank, and by the ability of the oil to separate from the entrained seawater.

Test Conditions

Flushing run	: A flushing run of 1 hr under light load conditions is carried out on a particular straight mineral oil
Duration	: 30 hr (continuous running)
Speed	: 1000 r.p.m.
B.m.e.p.	: 70 p.s.i. approx
Fuel	: Gas oil containing 1·0%w sulphur
Specific fuel cons	: 0·40 lb/b.h.p. hr
Injection timing	: 46° b.t.d.c.
Jacket coolant temp outlet	: 50° C
Sump oil temperature	: Uncontrolled (approx 50° C)
Oil in system	: 16 pints
Make-up oil added	: None
Rate of leakage of seawater	: 150 ml/hr
Total leakage	: Approx 50% of initial crankcase oil charge

Oil samples are taken for analysis at intervals throughout the test from the following :—

(*a*) The pressure side of the pump delivering oil to the engine.
(*b*) The bottom of the oil tank.

EMULSIONS OF SEAWATER IN ADMIRALTY FUEL OIL, WITH SPECIAL REFERENCE TO THEIR DEMULSIFICATION

By W. KILLNER *

THE method described by Gray and Killner [1] and Lawrence and Killner [2] for breaking seawater–fuel oil emulsions by the addition of surface active agents and heating has been successfully applied on board ships at sea and also on a larger scale in storage tanks at Admiralty fuel oil storage depots.

Experience has shown that many of the emulsions met with in service are heat stable. Heating may cause some water to separate, but it is only the water in large drops which, in the cold, are held in the oil or emulsion and fall out when the viscous resistance of the oil is lowered by heating. Prolonged heating will also free the upper layers of oil from water, due to the sedimentation of the emulsion, and this may go on until a tank contains three layers, *i.e.*, water which has been held up as large drops, emulsion which has sedimented, and oil free from water. Heating has not broken the emulsion, but merely caused it to sediment until it approaches the 74 per cent limit at which it remains.

In the earlier experiments it was realized that when using a surface active agent high temperature increases the rate of breaking and subsequent separation. It was, however, found that at 130° to 150° F the results obtained were about the same as those obtained at 180° F.

A maximum working temperature of 150° F also appeared to be a safe one from the point of view of the danger of liberation of volatile matter which may introduce risk of explosion.

Trials at Sea

The trials at sea were carried out in a tank approximately 16 ft deep with a capacity of some 30 tons. The tank was fitted with steam heating coils, and the connexions to the pump were arranged so that, amongst other things, the contents of the tank could be circulated by drawing from the bottom and discharging into the top.

Teepol was used as the surface active agent, and the amount added was sufficient to give a concentration of 0·1 to 0·2 per cent calculated on the total water present.

In all the trials carried out in ships the oil was circulated from bottom to top, and the Teepol was run slowly into the discharge. The circulation was continued long enough to ensure good mixing.

After mixing, heating steam was turned on and the contents of the tank held at a temperature of 130° to 150° F until the breaking of the emulsion and separation of the water was achieved. Samples of the oil were taken from time to time and the heating continued until the oil showed a water content of not more than 1·0 per cent. Emulsions containing from 4 to 20

* R.N.S.S., Principal Scientific Officer at the Admiralty Fuel Experimental Station.

per cent of water have been successfully treated in this manner, but in no case has separation of the water been achieved in less than 24 hr.

Trials at Fuel Oil Storage Depots

A trial at a fuel oil storage depot was carried out on 2500 tons of oil, contained in a 5000-ton tank. The water content was found to be 12·0 per cent at the top, rising to 17·6 per cent at the bottom, and the depth of the oil was 15 ft.

In this trial the requisite amount of Teepol was sprayed through a manhole on to the surface of the oil; it could not be incorporated into the oil by circulating or any other form of mixing.

The tank was heated by steam coils fitted at about 4 inches from the bottom. When the temperature of the oil was 160° F at the top, the Teepol was added and the heating steam shut off; the temperature at the bottom was observed to be 108° F.

After settling for five days, it was found that 85·3 per cent of the available oil present had a water content of not more than 1·0 per cent, and after a further five days 89·2 per cent of the available oil had a water content of not more than 1·0 per cent.

Treatment at 265° F

Although the process has proved successful in dealing with emulsions formed during the operation of the fuelling system in a ship, and also in dealing with wet oil which arises from various sources and is put into shore storage, it was evident that a much greater use could be made if a considerable speeding up of the process could be achieved.

As a result of further laboratory work, it has been shown that seawater–fuel oil emulsions containing sufficient Teepol to give a concentration of 0·1 to 0·2 per cent, calculated on the water present, will separate immediately when heated to about 265° F under a pressure sufficient to prevent the water from boiling. Laboratory trials on " wet " fuel, with water content ranging from 1 to 30 per cent, gave almost immediate separation of free water and dry oil at 265° F and 30 lb pressure.

A larger trial was carried out in a 50-gal cylindrical steel vessel fitted with :—

(1) sampling cocks every three inches;
(2) inlet pipe for introducing the emulsion;
(3) water discharge at the bottom and oil discharge at the top;
(4) steam coil for heating;
(5) tubes to carry thermocouples;
(6) pressure gauge and safety valve.

The vessel was filled with an emulsion containing 40 per cent of seawater, into which the requisite amount of Teepol had been added and mixed. Heating steam was turned on until the thermocouples recorded a temperature of 265° F, when the steam was shut off. The pressure was regulated at 30 lb by allowing excess to escape through the top oil sampling cock.

	Time	Temperature of oil	Pressure
Heating steam turned on .	3.25 p.m.	80° F	Atmospheric
Heating steam shut off .	3.55 p.m.	265° F	30 lb

When the steam was shut off, samples were taken from each of the cocks, and the water content of the oil was found to be less than 1·0 per cent throughout, and the water–oil interface was found to be as calculated. All samples were drawn off between 3.55 p.m. and 4.0 p.m.

This work indicated that, provided the requisite concentration of Teepol can be incorporated into an emulsion, subsequent heating to a temperature of about 265° F under a pressure of the order of 30 lb, an emulsion can be broken and the separation of dry oil and free water achieved in a few minutes.

Development of a Continuous Process

The work has thus led the way to a continuous process where emulsion can be fed in at one end of a plant and dry oil and separated water run off at the discharge end, and such a process has been developed.

From the laboratory work it was evident that the conditions which

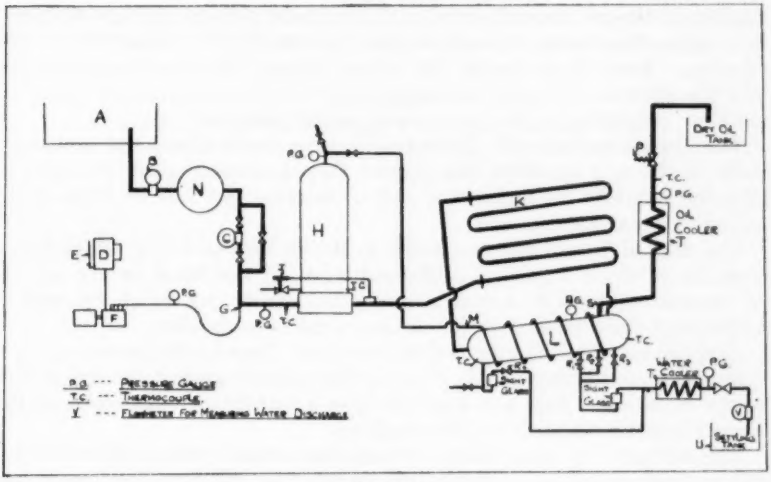


FIG 1

govern the breaking of an emulsion and the separation of the water at a rate which will allow the operation to be carried out as a continuous one are :—

(1) A knowledge of the amount of water actually passing through the pipeline, so as to enable the amount of Teepol to be added to give the correct concentration;

(2) The thorough incorporation into the emulsion of the requisite amount of Teepol;

(3) The heating of the mixture of wet oil and Teepol to a temperature of 265° F under a pressure sufficient to keep the water below its boiling point;

(4) The maintaining of the mixture at the requisite temperature and pressure for a period sufficiently long to allow the breaking of the emulsion and subsequent separation of the water, so as to give two definite layers, *i.e.*, dry oil and water free from oil.

A plant (Fig 1) was assembled from material available, and although it was by no means an ideal one, it enabled trials to be carried out at higher temperatures. These trials have shown that when working at about 265° F the breaking of the emulsion and the separation of the seawater and fuel oil was sufficiently rapid for the process to be operated continuously. Trials were carried out on emulsions containing from 3 to 30 per cent of seawater, and continuous runs of up to 4 hr were made; in these runs the water content of the oil was brought down to less than 1 per cent.

Although the highest flow rate achieved was 1½ tons/hr, there is reason to expect that considerably higher flow rates can be achieved in a properly designed plant based on the work reported in this paper.

Description of the Plant and Continuous Process

In order to determine the amount of water passing through the pipeline from the emulsion tank (A), an instrument (B), which gave a continuous reading of the per cent of water in the emulsion passing through the pipeline, and a flow meter (C), which gave the rate of flow, were put into the pipeline. From these figures the actual amount of water was obtained, and the amount of Teepol necessary to give a concentration of about 0·2 per cent, calculated on the water, was readily obtained.

The Teepol was suitably diluted with water, to facilitate the rapid estimate of the rate at which the diluted Teepol solution must be added to give the requisite concentration, and to increase the bulk of liquid to be added to a manageable rate.

The diluted Teepol was contained in the storage tank (D), which had a capacity of about 3 gal. A calibrated tube (E) was fitted on the outside of the storage tank to act as a measuring device, by which the rate of addition of the diluted Teepol solution could be controlled.

A variable pump (F) was used to pump the Teepol solution to a sprayer inserted in the pipeline at (G), to spray the solution against the line of flow of the emulsion. This was found to give a satisfactory dispersion of the Teepol solution throughout the emulsion.

The mixture was then passed through the normal type of oil fuel heater (H) to bring it up to a temperature of 265° to 270° F. The heater was fitted with a Drayton regulator (J) to keep the discharged mixture at the required temperature.

The heater discharged into a coiled pipe (K), 100 ft long and 2½ inches bore, connected to a cylindrical vessel (L), about 5 ft long and 1 ft diameter, set at an angle of about 25 degrees. The coiled pipe and cylindrical vessel were lagged, and the latter was also heated by a steam coil (M), using the waste steam from the oil fuel heater. Passage through the coiled pipe, while still held at a high temperature and under pressure, gave the time necessary for separation to take place, and the cylindrical vessel provided facilities for drawing off the separated water and the dry oil.

Four cocks (R1–R4) were fitted along the bottom of the cylindrical vessel to enable the separated water to be drawn off at different levels, sight glasses were fitted in the line through which the separated water passed, to provide visual means of control of water and oil discharge. The dry oil was discharged at (S) at the upper end of the cylindrical vessel, the

rate of discharge being automatically regulated by the spring-loaded valve (P).

Both the discharged water and dry oil passed through cooling coils (T) before being discharged into their respective tanks.

It was found that the separated water had a tendency to carry some small globules of oil with it. This water was therefore discharged into a settling tank (U), where the drops of oil readily separated.

A pressure of at least 30 p.s.i. was maintained throughout the whole plant by means of the pump (N) and the spring-loaded valve (P), to keep the mixture below the boiling point of water.

Acknowledgments

The author gratefully acknowledges the valuable help of the Royal Naval Engineer Officers at the Admiralty Fuel Experimental Station, in the designing and operating of the plant for the continuous process, and also records his thanks to the Admiralty for permission to publish this work.

References

[1] Gray, C. J., and Killner, W. *Trans. Inst. Mar. Engrs*, 1948, **60**, 43–54.
[2] Lawrence, A. S. C., and Killner, W. *J. Inst. Petrol.*, 1948, **34**, 821–56.

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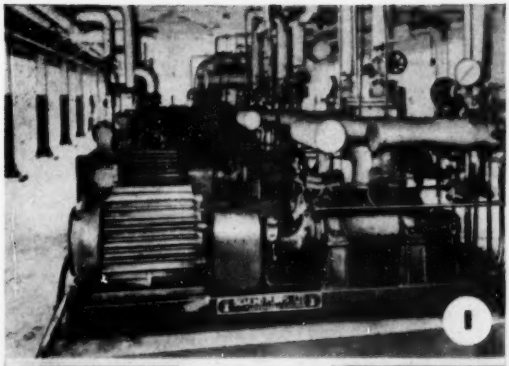

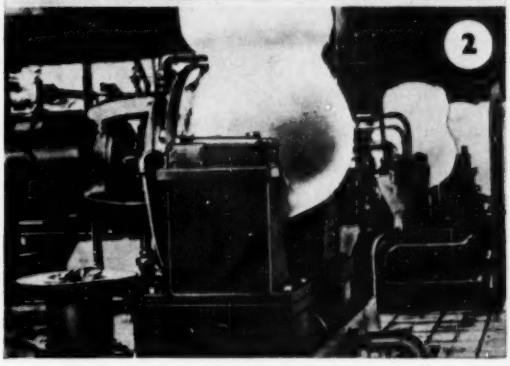

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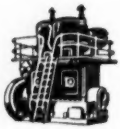

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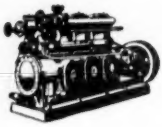

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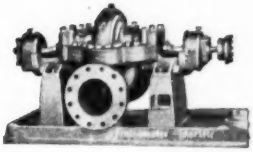

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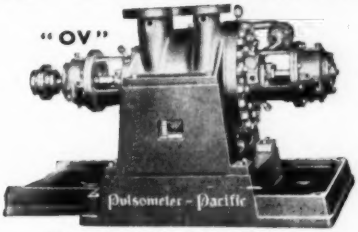

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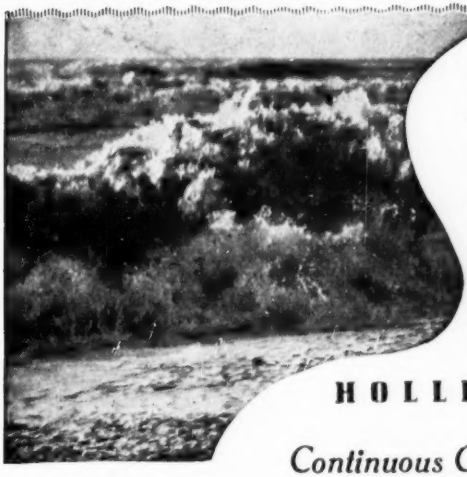

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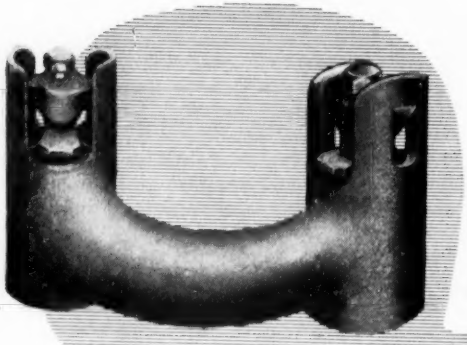

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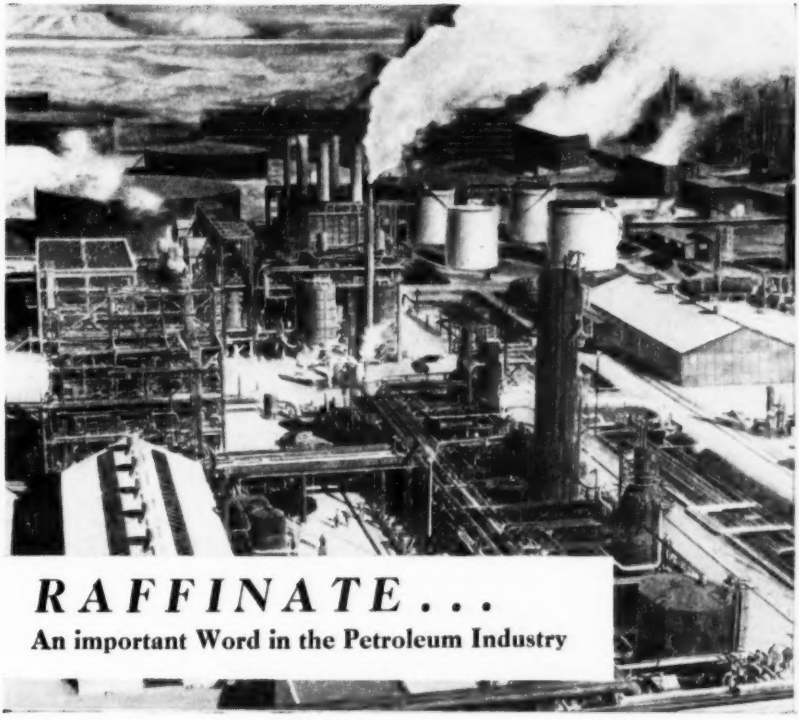

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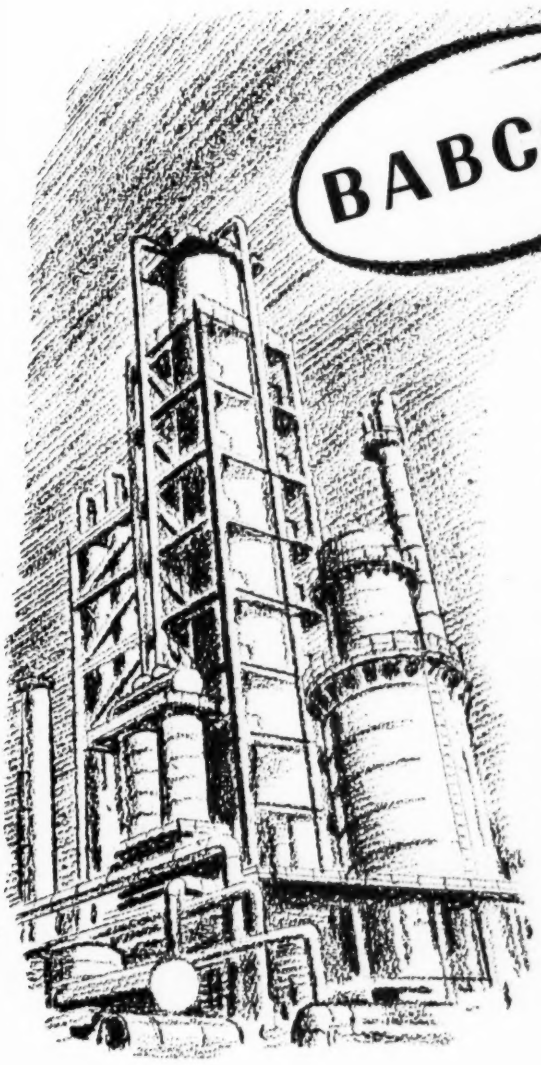

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The photograph shows columns on the Distillation Unit, M.E.C. project, Shell Haven, England.

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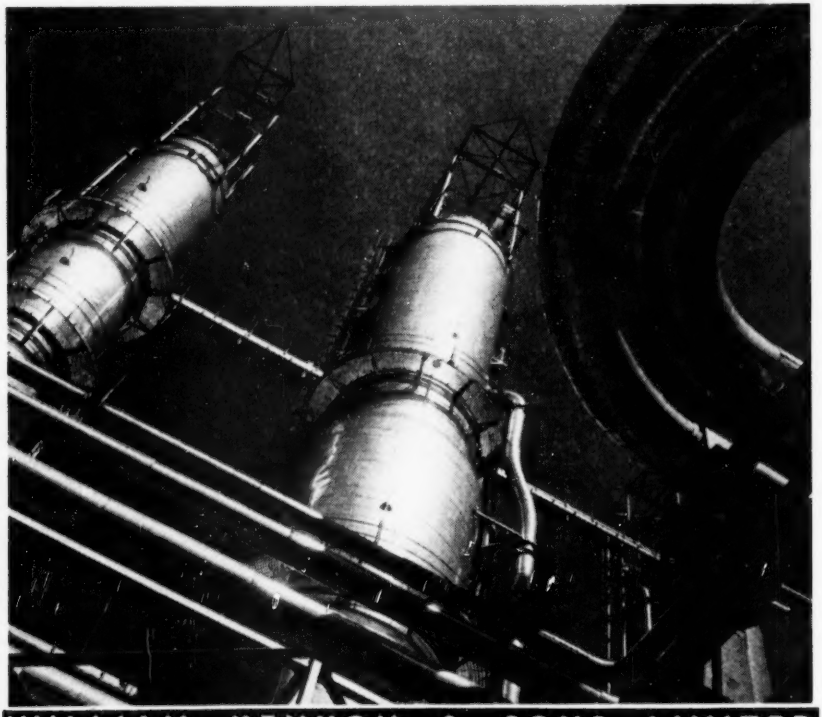

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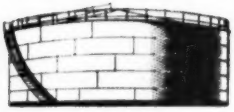

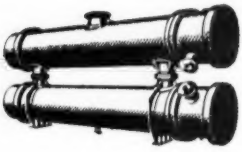

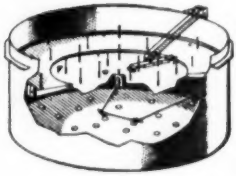

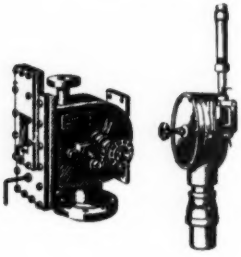

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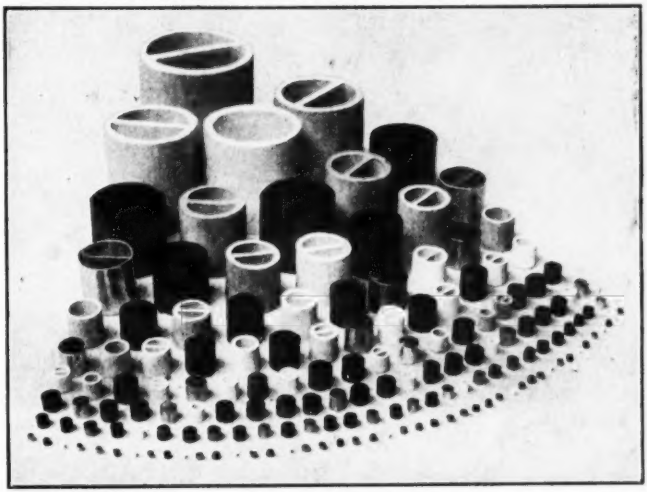

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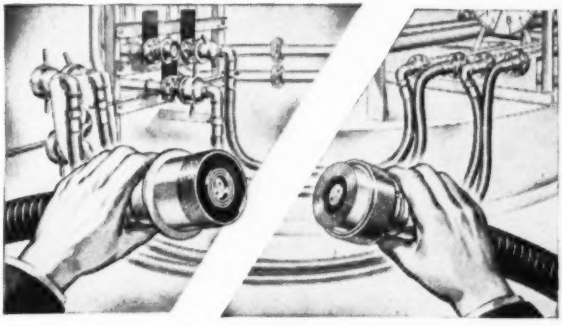

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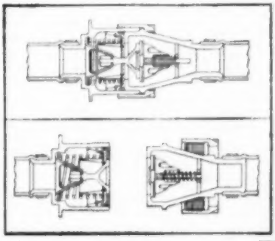

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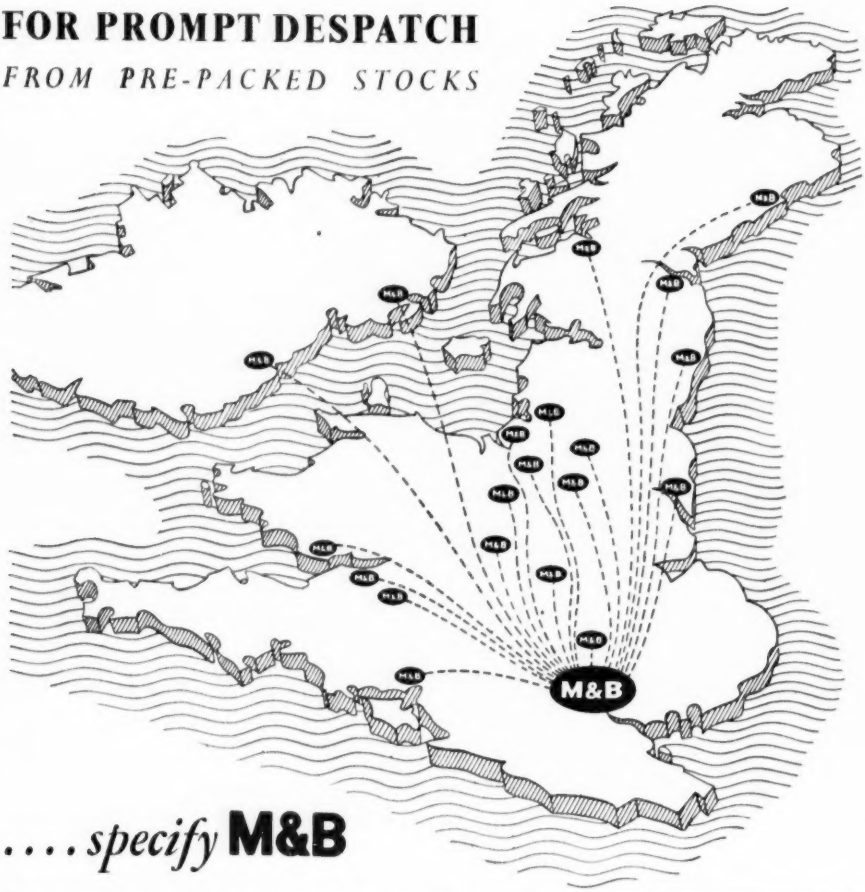

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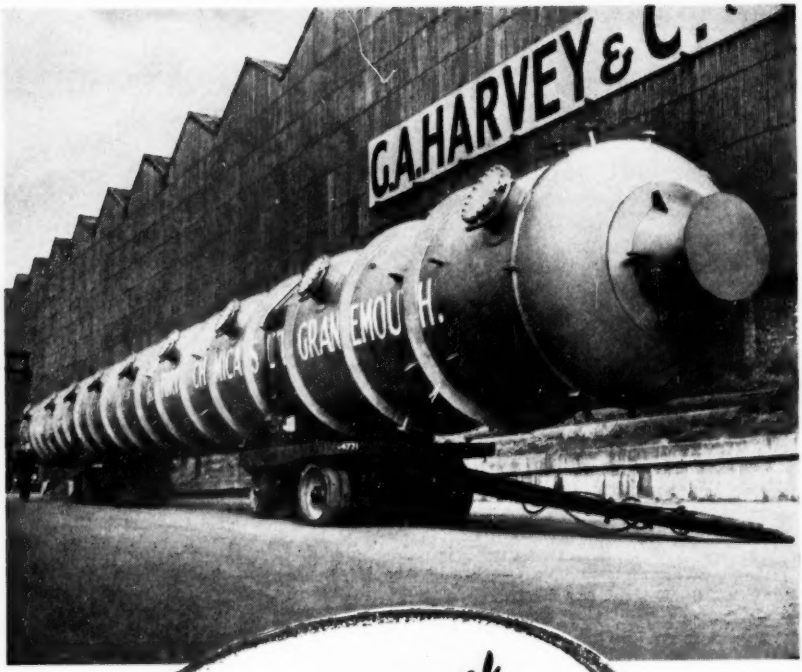

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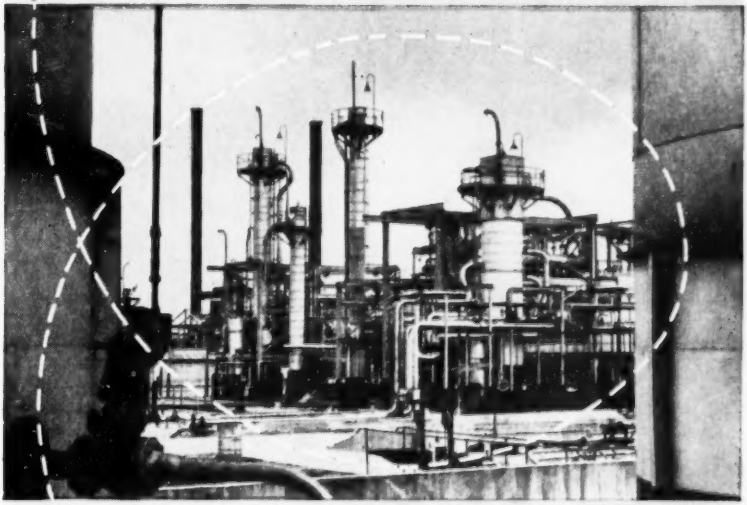

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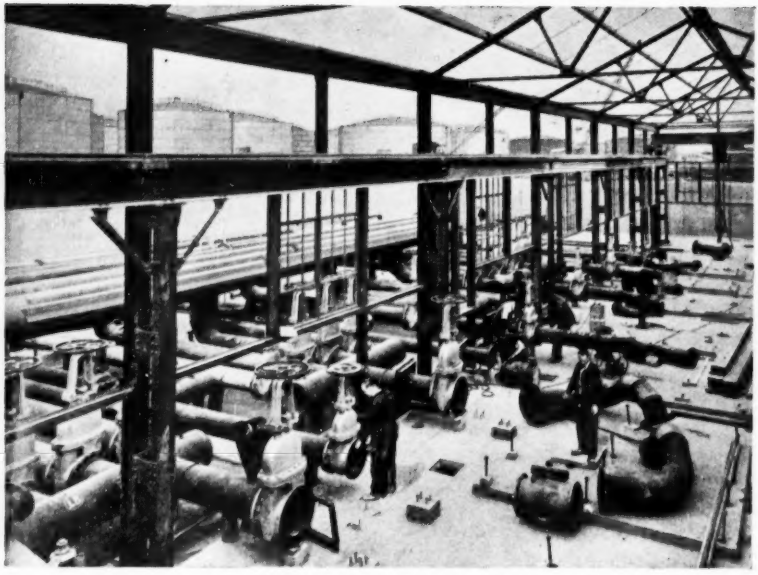

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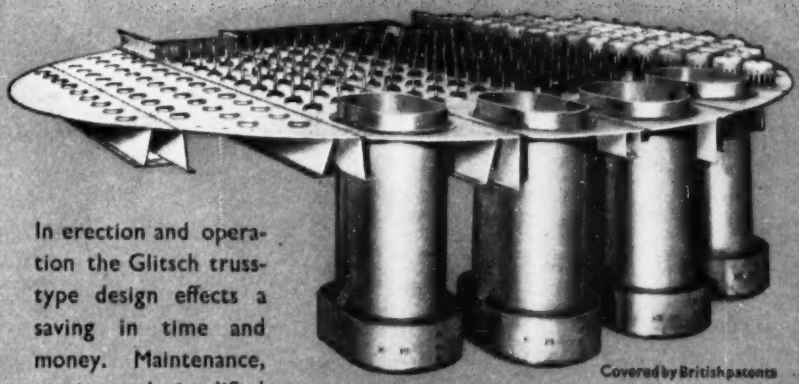

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